Physical Conditions in Low Ionization Regions of the Orion Nebula

J.A. Baldwin, A. Crotts, R.J. DuFour, G.J. Ferland, S. Heathcote, J.J. Hester, K.T. Korista, P.G. Martin, C.R. O'Dell, R. Rubin, A.G.G.M. Tielens, D.A. Verner, E.M. Verner, D. Walter, Z. Wen

Abstract

We reexamine the spectroscopic underpinnings of recent claims that low ionization [OI] and [FeII] lines from the Orion HII region are produced in a region where the iron-carrying grains have been destroyed and the electron density is surprisingly high. Our new HST and CTIO observations show that previous reported detections of [OI] λ5577 were strongly affected by telluric emission. Our line limits consistent with a moderate density ($\approx 10^4$ cm^{-3}) photoionized gas. We show that a previously proposed model of the Orion HII region reproduces the observed [OI] and [FeII] spectrum. These lines are fully consistent with formation in a moderate density dusty region.

1. Introduction

The Orion Nebula is the defining blister HII region (Zuckerman 1973; Balick et al. 1974). A star cluster ionizes the skin of the molecular cloud, causing an expansion away from the molecular cloud towards us. The general picture is that the HII region is in photoionization equilibrium, the gas is a hydrodynamic flow with a characteristic density in concert with that deduced for the background photodissociation region (Tielens & Hollenbach 1985), and the region is dusty with high depletions of the refractory elements (Rubin, Dufour, & Walter 1993).

In a recent series of papers Bautista, Pradhan, & Osterbrock (1994; hereafter BPO), Bautista & Pradhan (1995; hereafter BP), and Bautista, Pradhan, & Peng (1996; hereafter BPP) have claimed that [OI] and [FeII] lines are produced by a warm ($T_e \approx 10^4$ °K) region with very high electron density ($n_e \sim 2 \times 10^6$ cm^{-3}) and a solar iron abundance. This is surprising since kinematics pinpoint the physical location of low-ionization emission (O'Dell & Wen 1992), and photoionization equilibrium demands that any very dense gas have a low ionization parameter and thus be cold. The solar gas phase iron abundance is surprising for such a dusty environment but would have important implications for grain destruction mechanisms.

Here we use better spectroscopic data and new photoionization calculations to reexamine these claims.

2. The [OI] Spectrum

BP's claims of the existence of a very dense region within the Orion blister were based on their reanalysis of the [OI] intensities reported by Osterbrock, Tran, & Veilleux (1992; hereafter OTV) and Baldwin et al (1991; hereafter BFM). We will show that the [OI] auroral line (λ5577) detected by OTV and BFM are actually telluric emission, as indicated by BFM. There can be telluric contamination of the nebular line as well (O'Dell & Wen 1992). The BFM measurement of [OI] λ6300 also appears to include [SIII] λ6312.

We observed two positions in the Orion Nebula with the Faint Object Spectrograph on the Hubble Space Telescope (HST) using the 0.86″ diameter circular aperture on 1995 October 23/24 (UT) as part of the Cycle 5 program GO-6056. Here we report the results of two 225 sec integrations with the red digicon and G570H grating with the aperture located at positions 1SW (J2000 RA, DEC) = (05h35m14.7s, -05d23'41.5") and x2 (05h35m16.92s, -05d23'57.5"), both about 1 arcmin SW of θ^1 Ori C. The two spectra were summed and are presented in Figure 1. Line fluxes were measured with Gaussian fits to the profiles and are presented in Table 1 where they are given relative to HeI 6678 and are uncorrected for interstellar extinction. We note that the HST FOS spectra are not affected by telluric emission. Also, we point out that there seems to be a bad diode "glitch" between [Cl III] 5538 and [OI] 5577 in the flat fields, but that this does not impact our analysis.

The CTIO spectrum was taken with the Cassegrain echelle spectrograph on the 4m Blanco Telescope, on 12 January 1996. This provided a 11 km s^{-1} resolution spectrum at a time when the Earth's motion split the nebular lines from the telluric emission. The spectra were extracted over a slit width of 1" and length of 12.5", centered on the BFM position 1. The line intensities are in Table 1 and parts are shown in Figure 1. Orion has a spectrum with a strong point to point variation (Peimbert & Torres-Peimbert 1977), and this accounts for the differences in the two spectra. The [NII] and [SII] spectra show the BFM position has the higher ionization.

Limits to the [OI] ratio (6300+6363)/ 5577 are needed to set n_e for an assumed T_e. Table 2 gives reddening corrected intensities relative to Hβ, using BFM's extinction for CTIO, and c=0.507 for HST (Costero & Peimbert 1970). The CTIO data in Table 1 were renormalized using the HeI 6678 intensity reported in BFM. The observed limits are >84 (CTIO) and >33 (HST) and the reddening corrected intensities are >71 and >29. This is very different from the ratio of 22 adopted by BP. The CTIO [SII] 6716/6731 ratio (0.53) indicates a temperature independent density of ~6600 cm^{-3} (Osterbrock 1989) . The [NII] 5755/6548 ratio indicates a temperature of 10,100 °K, fairly independent of density in this range. The HST-derived properties are similar. Assuming 10^4 °K the CTIO [OI] ratio limit sets the limit $n_e < 1.6\times10^5$ cm^{-3}, consistent with the [SII] density and much lower than the density deduced by BP. Assuming n_e([SII]) we find that the [OI] ratio limit sets the limit T_e < 11,600 °K, consistent with the [NII] spectrum. These are all conventional Orion HII region numbers, and we conclude that the [OI] spectrum is consistent with its formation in moderate density gas.

We recomputed the BFM model for the CTIO position (Table 2). We used the exact BFM parameters: depleted elements (including iron with $Fe/H=3\times10^{-6}$), grains, ionization by the central star, and a hydrostatic blister. We reused the

Kurucz (1979) continuum, even though recent hydrodynamic stellar atmospheres reproduce high ionization lines of HII regions better (Sellmaier et al. 1996). A more detailed model will be the subject of a future paper. The model predicts an [OI] ratio of 102.

3. The[FeII]spectrum

We incorporated a 371 level FeII model atom into Cloudy (Ferland et al. 1996; Verner et al. 1996). Collision data for our model atom are from Zhang & Pradhan (1995), radiative data from Nahar (1995), Johansson et al. (1995), Giridhar & Arellano Ferro (1995), Fuhr, Martin, & Wiese (1988), Fawcett (1987), and Kurucz (1981), and energy levels from Johansson (1994). More recently, Bautista & Pradhan (1996) have produced new calculations of the FeII collision strengths, and for the 595 transitions in common, 66% of the data differ from Zhang & Pradhan (1995), which we used here, by more than a factor of two. We take this to represent the uncertainties in these calculations. This comparison also indicates that detailed deductions of physical conditions based on single lines ratios can be quite uncertain.

In our calculations a cloud is divided into a few hundred zones, T_e and the ion distribution are determined self-consistently, and the emission is determined for the local optical depths. Our primary goal is to model the broad lined regions of active galactic nuclei (Verner et al. 1995; and in preparation) —we incorporated all of the physics described by Wills, Netzer, & Wills (1985). We include line overlap pumping by all $\approx 10^4$ emission lines included in Cloudy, by FeII line overlap, and by the incident continuum. We verified that the FeII atom goes to LTE in the high-density limit, and that in the low density limit each excitation is followed simply by radiative cascades.

We attempted to reproduce the BPO results with only mixed success. Computing their isothermal-isochoric model with the same atomic data, we do reproduce the [FeII] line intensity ratio $I(5262)/I(8617)$ (Figure 2*a* of BPO and

Figure 3*b* of BPP), but it is clear that the line intensity ratio *I*(5334)/*I*(8892) shown in Figure 2*b* of BPO is incorrect. The high-density limit of a line ratio in the collisional-radiative model can be easily obtained analytically. In a general form, the line ratio is $I_1 / I_2 = n_{u1} A_{u1,l1} h\nu_1 / n_{u2} A_{u2,l2} h\nu_2$, where u_i and l_i stand for the upper and lower levels of the transitions, n_i are level populations, $h\nu_i$ energies of lines, A_{ij} transition probabilities, and the forbidden lines are optically thin. In the high-density limit, level populations are determined by the Boltzmann equation. For the 5334 line, $g_u = 10$, $E_u = 21582$ cm^{-1}, $E_l = 2838$ cm^{-1}, $A_{ul} = 0.26$ s^{-1}. For the 8892 line, $g_u = 4$, $E_u = 13673$ cm^{-1}, $E_l = 2430$ cm^{-1}, $A_{ul} = 0.011$ s^{-1}. Substituting these numbers we find that the high-density limit for *I*(5334)/*I*(8892) would be 19.4, 27.8, and 38.2 respectively at $T_e = 7000$, 9000, and 12,000 K. In the Figure 2*b* of BPO, this line ratio decreases with increasing density, and actually becomes less than 0.2 for all the three temperatures at $n_e > 10^7$ cm^{-3}. This is physically impossible. Note that although BPO discuss *I*(5334)/*I*(8892) in the text, and the vertical axis caption of their Figure 2*b* and the plotted observed ratios also indicate this line ratio, the caption to Figure 2 calls it the *I*(5262)/*I*(5159) ratio; this is clearly inconsistent. A similar consideration shows that the *I*(5262)/*I*(5159) line ratio also contradicts Figure 2*b* of BPO.

In the subsequent paper by BPP, pumping by incident continuum is included, and their equation is correct in the optically thin limit. However, the ultraviolet lines used for the pumping are usually optically thick and line self-shielding must be included if energy is to be conserved. In our treatment we follow Ferland (1992). The correct formulation of the constant temperature problem outlined in BPP should include the column density as an additional free parameter. Figure 3*b* of BPP shows the *I*(5262)/*I*(8617) line intensity ratio, which we can reproduce in a single zone constant temperature model, but the line ratio given in Table 2 of BPP at $n_e = 2 \times 10^6$ cm^{-3} contradicts their Figure 3*b*.

Based on such considerations, we felt that it would be worthwhile to reexamine the physical conditions in the FeII region. We recomputed the BFM model, but with our model FeII atom included. The [FeII] predictions listed in Table 2 are not directly comparable with BPP since T_e and n_e are the depth-dependent and self-consistent results of the solution of the equations of thermal and statistical equilibrium. Note that the BFM model is objective (uncontrived) in the sense that it was derived to reproduce the higher ionization lines and not low ionization species such as [OI] or [FeII]. Given the uncertainties in the collision strengths, model parameters, and point to point variations, this model reproduces the observed [FeII] spectrum quite well. Even with solar abundances, iron is not a major coolant in Orion, and the intensities of [FeII] lines scale linearly with abundance. If solar iron were used rather than the strongly depleted abundance we assumed, the [FeII] lines would be roughly 20 times too strong relative to the rest of the spectrum.

4. Conclusions

Previous detections of [OI] λ5577 were affected by telluric emission. Our new limits to the line sets limits on the density and temperature consistent with the physical conditions inferred from the other low ionization lines, such as [NII], [SII], and [OII], and does not provide evidence for the existence of a new high-density region.

We modeled the [FeII] spectrum using the parameters found by BFM, and predict a spectrum in good overall agreement with observations, certainly within the uncertainties. The (depleted) iron abundance of 3×10^{-6} given in BFM and used here was based on a single optical [FeIII] line. This is close to the value of Fe/H ~ 2.7×10^{-6} found by Erickson et al (1989, and in preparation) from KAO observations of the ground state [FeIII] 22.9μm line. The [FeII] lines predicted here confirm the depleted abundance suggested by the [FeIII] spectrum.

This work is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the STScI, which is operated by the AURA, Inc., under NASA contract NAS5-26555. We thank STScI for its support through grants GO-

4385, GO-5747, and GO-6056. RJD and GJF acknowledge NASA/Ames Research Center Interchange Grants NCC2-5008 and NCC2-5028, respectively. Research in Nebular Astrophysics at the University of Kentucky is supported by the Nation Science Foundation through award AST 93-19034.

Table 1 New Observations

Ion	Wavelength	CTIO[a]	HST[b]
[Cl III]	5518	-	0.106
[Cl III]	5538	0.13	0.119
[O I]	5577	<0.003	<0.0128
[O I]	5577 sky	0.044	
[NII]	5755	0.17	0.322
He I	5876	3.22	3.44
[O I]	6300	0.19	0.313
[O I]	6300 sky	0.0071	
[S III]	6312	0.49	0.565
Si II	6347	0.042	
[O I]	6364	0.063	0.113
Si II	6372	0.022	
[N II]	6548	3.30	7.35
$H\alpha$	6563	76-113[c]	85.2
[N II]	6583	11.4	21.0
He I	6678	1.00	1.00
[S II]	6716	0.52	0.865
[S II]	6731	0.98	1.75

[a] New CTIO echelle data at BFM position 1. Not dereddened.

[b] HST observations. Not dereddened.

[c] Poorly calibrated because of broad $H\alpha$ absorption in standard star

Table 2 - Dereddened and Predicted FeII Spectrum[a]

	Line	Ref	100 I(Obs)/Hβ	100 I(Calc)/Hβ
[FeII]	4244+4245	2	0.0580	0.0964
[FeII]	4277	2	0.0426	0.0266
[FeII]	4287	2	0.0855	0.0467:[b]
[FeII]	4815	2	0.0622	0.0526
[FeII]	5159+5158	2	0.0874	0.0882
[FeII]	5262	2	0.0540	0.0176
[FeII]	5334	2	0.0217	0.0162
[OI]	5577	3	<0.0136	0.00465
[NII]	5755	3	0.763	0.937
[OI]	6300	3	0.722	0.36
[NII]	6583	3	41.6	47.2
[SII]	6716	3	1.85	1.45
[SII]	6731	3	3.47	2.90
[FeII]	7155	2	0.0977	0.0114:[b]
[FeII]	7453	2	0.034	0.0035:[b]
[FeII]	8617	2	0.0665	0.145
[FeII]	8892	2	0.0129	0.0460
[FeII]	12567	1	0.4::	0.79
[FeII]	12703	1	0.1::	0.049
[FeII]	12941	1	0.2::	0.11
[FeII]	13278	1	0.2::	0.065

[a]Model calculations for the parameters given by BFM.

[b]Collison data are not available for these transitions so the Mewe (1972) $\bar{g}$ approximation is used instead.

Data references: 1) Lowe et al. 1979, 2) OTV, 3) new CTIO.

5. References

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).

Balick, B., Gammon, R., & Hjellming, R., 1974, Publ. A.S.P. 86, 616.

Bautista, M. A., & Pradhan, A. K. 1995, ApJ, 442, L65 (BP).

Bautista, M. A., & Pradhan, A. K. 1996, A&AS, 115, 551.

Bautista, M. A., Pradhan, A. K., & Osterbrock, D. E. 1994, ApJ, 432, L135 (BPO)

Bautista, M. A., Peng, J., & Pradhan, A. K. 1996, ApJ, 460, 372 (BPP).

Costero, R. & Peimbert, M., 1970, Bull. Obs. Ton. y Tacu, 5, 229

Erickson, E.F., Rubin, R.H., Haas, M.R., Simpson, J.P., & Colgan, S.W., 1989, BAAS 21, 1156.

Fawcett, B. C. 1987, Atomic Data Nucl. Data Tables, 37, 333

Ferland, G. J. 1992, ApJ 389, L63.

Ferland, G. J., Korista, K., Verner, D. A., Ferguson, J. W., Kingdon, J., & Verner, E.M. 1996, Publ. A.S. P. to be submitted.

Fuhr, J. R., Martin, G. A., & Wiese, W. L. 1988, J. Phys. Chem. Ref. Data, 17, Suppl. 4

Giridhar, S., & Arellano Ferro, A. 1995, Rev. Mexicana Astron. Astrof., 31, 23

Johansson, S. 1994, private communication

Johansson, S., Brage, T., Leckrone, D. S., Nave, G., & Wahlgren, G. M. 1995, ApJ, 446, 361.

Kurucz, R. L. 1979, ApJS, 40, 1.

Kurucz, R. L. 1981, Smithsonian Astrophys. Obs. Rep. 390.

Lowe, R.P., Moorehead, J. M., & Wehlau, W.H., 1979, ApJ, 228, 191.

Mewe, R., 1972, A&A 20, 215.

Nahar, S. N. 1995, A&A, 293, 967

O'Dell, C.R., & Wen, Z., 1992, ApJ 387, 229.

Osterbrock, D. E., 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei, (University Science Books, Mill Valley, California).

Osterbrock, D. E., Tran, H. D., & Veilleux, S. 1992, ApJ, 389, 305 (OTV).

Peimbert, M., & Torres-Peimbert, S., 1977, MNRAS 179, 217.

Rubin, R.H., Dufour, R.J., &Walter, D.K., 1993, ApJ 413, 242.

Sellmaier, F.H., Yamamoto, T., Paulrach, A.W.A., & Rubin, R.H. 1996, A&A, 306, L37.

Tielens, A.G.G.M., & Hollenbach, D., 1985, Ap.J 291, 722.

Verner, E. M.,. Ferland, G.J., Korista, K.T., & Verner, D. A., 1995, BAAS 27, 840.

Verner, E. M., et al. 1996, in preparation.

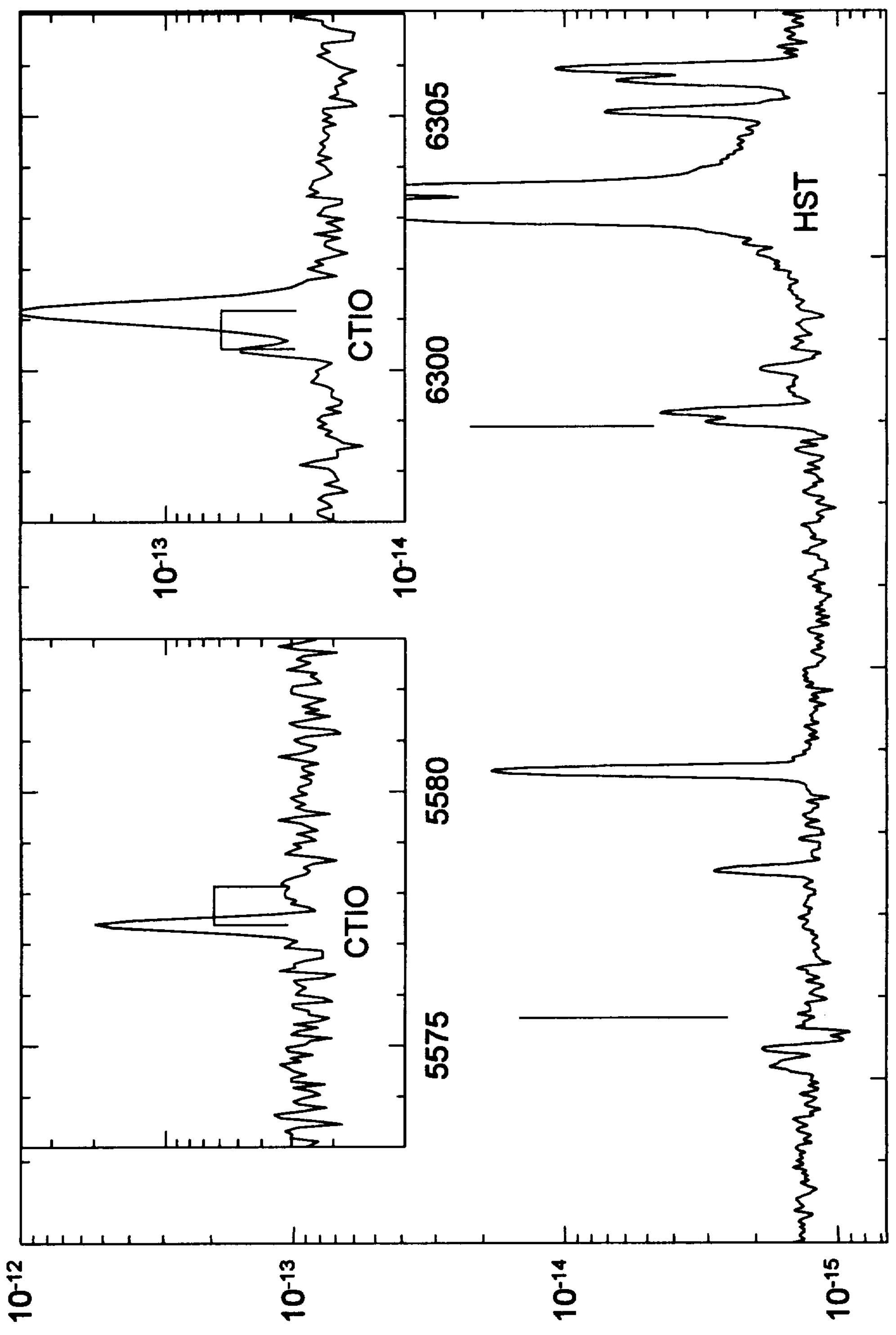
Wills, B. J., Netzer, H., & Wills, D. 1985, ApJ, 288, 94

Zhang, H. L., & Pradhan, A. K. 1995, A&A, 293, 953.

Zuckerman, B., 1973, ApJ 183, 863.

6. Figure Caption

Figure 1 The spectrum of the Orion Nebula observed with the HST FOS and the CTIO 4m echelle. The lower half shows the HST spectrum. The two inserts show portions of orders 9 and 21 on the echelle spectrum. Tickmarks indicate the positions of the nebular [OI] lines in all spectra, and in the inserts also show the position of the telluric [OI] lines just to the left of the lines produced in the nebula.


10-12
10-13
10-14
10-15
5500
6000
6500
HST
CTIO
5575
5580
10-13
10-14
CTIO
6300
6305