[Fe II] EMISSION FROM HIGH-DENSITY REGIONS IN THE ORION NEBULA\textsuperscript{1}

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ABSTRACT

Direct spectroscopic evidence of high-density regions in the Orion Nebula, \(N_e \approx 10^5\)–\(10^7\) cm\(^{-3}\), is obtained from the forbidden optical and near-IR [Fe II] emission lines, using new atomic data. Calculations for level populations and line ratios are carried out using 16, 35, and 142 level collisional-radiative models for Fe II. Estimates of Fe II abundances derived from the near-infrared and the optical line intensities are consistent with a high density of \(10^6\) cm\(^{-3}\) in the [Fe II] emitting regions. Important consequences for abundance determinations in the nebula are pointed out.

Subject headings: ISM: abundances — ISM: individual (Orion Nebula) — ISM: structure

1. INTRODUCTION

The Orion Nebula (M42) is the best-studied H II region in our Galaxy, on which every observational technique has been tested and used (e.g., Felli et al. 1993; O'Dell, Wen, & Hu 1993, and references therein). Optical and radio studies of this nebula show many dense knots, filaments, and other structures, including externally ionized “dense globules” (Dyson 1968), “partly ionized globules” (Pastor, Cantó, & Rodríguez 1991), “compact sources” (Garay, Moran, & Reid 1987; Felli et al. 1993), and “protoplanetary disks or protopylads” (O'Dell et al. 1993). All these features are superposed on larger scale variations in density (e.g., Pogge, Owen, & Atwood 1992). In addition, there is an ionization front at the “edge” of the ionized blister in the denser molecular cloud (Rubin et al. 1991).

Previous density determinations in the Orion Nebula, usually using “standard” intensity ratios of the [O II] \(\lambda\lambda 3729, 3726\) and [S II] \(\lambda\lambda 6716, 6731\) lines (Seaton & Osterbrock 1957; Pogge et al. 1992), indicate wide electron density variations over the range \(10^2\)–\(10^4\) cm\(^{-3}\). These ratios are relatively insensitive to higher densities, but the high-resolution direct images and maps mentioned above show structures of sizes down to the limit of resolution. In addition, abundance derivations are affected by the density structure, and hence are difficult to obtain accurately. For example, recently Osterbrock, Tran, & Veilleux (1992, hereafter OTV) analyzed the optical and near-IR [Fe II] emission lines in the Orion Nebula, and found considerable scatter in the Fe II abundance as derived from the faint lines. As discussed by OTV, the main problem was the lack of atomic data for Fe II of adequate precision. In the present Letter we employ new collisional and radiative data, and much more extensive collisional-radiative (CR) models for Fe II than in previous studies, to reanalyze the optical and IR lines from the Orion Nebula. This analysis shows that the optical lines provide direct evidence of dense regions, and that the abundances so derived are consistent with the high densities.

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Extensive new collisional and radiative data have been calculated as part of the IRON Project (Hummer et al. 1993) by the Ohio State group: electron impact excitation rates for 10,011 IR, optical, and UV transitions among 142 levels in Fe II (Zhang & Pradhan 1994), and radiative transition probabilities for over 20,000 dipole transitions (Nahar 1994). Some of the new data were described by Pradhan & Zhang (1993) and employed to calculate IR line ratios in [Fe II]. Significant differences from the previously available collision strengths of Nussbaumer & Storey (1980) and Keenan et al. (1988) were noted.

2. THE COLLISIONAL-RADIATIVE MODEL

We approximate the mean conditions in the observed region by a single temperature and density. Figure 1 shows schematically the energy levels considered in the present work. As functions of electron density the [Fe II] IR lines saturate at \(N_e > 10^4\) cm\(^{-3}\) (as do the density-sensitive line ratios [O II] and [S II]) since the level populations of the associated low-lying levels approach statistical equilibrium (Pradhan & Zhang 1993). On the other hand, the forbidden optical [Fe II] lines with radiative transition probabilities generally 2–4 orders of magnitude higher have much higher critical densities. The lower group of 16 fine-structure levels of the first four LS terms, \(a^6D, a^4D, a^4P, a^4F\), yield most of the observed IR lines. Transitions from the next higher group of quartet even-parity levels \(a^2H\) through \(b^4P\), to the lower group, give rise to most of the observed [Fe II] lines in the optical region. The odd-parity levels arising from the higher configuration \(3d^4p\) give rise to UV transitions, in particular the strong UV multiplets \(a^6D-z^6D, z^6F, z^6P\).

The present work considers three CR models, including 16, 35, and 142 Fe II levels, respectively. The collision strengths in these models are taken from Pradhan & Zhang (1993) and Zhang & Pradhan (1994), the transition probabilities for the forbidden transitions are taken from Nussbaumer & Storey (1980) and Garstang (1962), and for the allowed transition from Nahar (1994). The analysis in the present work is based primarily on the 35 level model, which yields both the optical and the IR line ratios. However, consistency and convergence
checks are provided by the 16 and the 142 level models. Although we have computed the collisional data and the radiative rates for allowed transitions for the 142 level case, these data sets are still incomplete in terms of the high-lying forbidden transitions and couplings to the doublet and the sextet states to form a full CR model. The analysis of the IR, optical, and UV transitions would thus require a further extension of the present work.

The forbidden lines of interest in the density analysis are shown in Figure 1.

3. ANALYSIS AND RESULTS

In this section we present density and temperature diagnostics of Orion based on the observed optical [Fe II] emission lines. These line ratios reveal high-density regions, with $N_e \approx 10^6$ cm$^{-3}$ ($T = 10,000$ K), as the regions in the nebula which tend to dominate the [Fe II] emission. We begin with a reexamination of previous diagnostic studies by OTV, and their determination of the relative Fe$^+$ abundances, obtained using the temperature and electron density derived from several ionic species of N, O, S, Cl, and Ar. Then, presenting a comparison of the calculated and observed optical [Fe II] line ratios, we show that these are more consistent with high-density conditions ($N_e \approx 10^6$ cm$^{-3}$) than the earlier deduction of much lower densities. Finally, the results are compared with other independent infrared [Fe II] observations of the nebula.

In their work OTV describe the observations of weak [Fe II] optical emission just north of the Trapezium in NGC 1976 using a rectangular slit aperture of width of 2$^\prime$ for $\lambda \leq 7000$ Å, and 3$^\prime$ for $\lambda \geq 7000$ Å. The slit was oriented east-west, centered 58$^\prime$ north, 1.8 s east of $\theta^1$ Ori C. The relative intensities of the detected [Fe II] lines, after correcting for extinction, are given in Table 1. With the forbidden lines of [N II], [O III], [O IV], [S III], [S II], [C II], and [Ar IV] for density and temperature diagnostics, OTV determined $N_e = 4000$ cm$^{-3}$, $T = 9000$ K. The relative abundances of Fe$^+$ with respect to H$^+$ assuming these conditions are shown in the column labeled (A) in Table 1. There are two near-infrared [Fe II] lines which give basically one result, $N(Fe^+)/N(H^+)$ = $(0.36 \pm 0.12) \times 10^{-7}$, taking a straight average, while the six optical [Fe II] lines give a signifi-

<table>
<thead>
<tr>
<th>$\lambda$ (Å)</th>
<th>$I(\lambda)/I(\text{H}_\alpha)$</th>
<th>$N(\text{Fe}^+)/N(\text{H}^+)$ ($\times 10^7$)</th>
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</thead>
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<tr>
<td>8617</td>
<td>$a^4\text{Fe}_2^+ - a^6\text{Fe}_2^+$</td>
<td>1.00</td>
</tr>
<tr>
<td>8892</td>
<td>$a^4\text{Fe}_2^+ - a^6\text{Fe}_2^+$</td>
<td>0.20</td>
</tr>
<tr>
<td>5159</td>
<td>$a^4\text{Fe}_2^+ - a^6\text{Fe}_2^+$</td>
<td>0.82</td>
</tr>
<tr>
<td>5262</td>
<td>$a^4\text{Fe}_2^+ - a^6\text{Fe}_2^+$</td>
<td>1.5</td>
</tr>
<tr>
<td>5334</td>
<td>$a^4\text{Fe}_2^+ - a^6\text{Fe}_2^+$</td>
<td>0.82</td>
</tr>
</tbody>
</table>

* $I(8617)/I(H_\alpha)$ = $2.37 \times 10^{-4}$.

* (A) $T = 9000$ K, $N_e = 4000$ cm$^{-3}$; (B) $T = 9000$ K, $N_e = 10^5$ cm$^{-3}$; (C) $T = 9000$ K, $N_e = 10^6$ cm$^{-3}$; (D) $T = 9000$ K, $N_e = 10^7$ cm$^{-3}$; (E) $T = 10,000$ K, $N_e = 10^6$ cm$^{-3}$.
Fig. 2.—[Fe ii] line ratios vs. log N_e (cm\(^{-3}\)) for T = 9000 (solid line), 7000 (dotted line), and 12,000 K (dot-dashed line); (a) optical to near-IR line ratio I(5262)/I(8617), and (b) optical to optical ratios I(5262)/I(5159). The observed line [Fe ii] line ratios in Orion suggest N_e \approx \times 10^4 \text{ cm}^{-3} \text{ and } T \approx 9000 \text{ K.}

Significantly different result, N(Fe^+)/N(H^+) = (2.2 \pm 1.0) \times 10^{-7}. This is a discrepancy by a factor 6.1, much larger than the combined observational and theoretical uncertainties (the latter from the collision strengths and transition probabilities). It may indicate that the assumed physical conditions are not correct.

Large uncertainties in the OTV observations may be ruled out as follows. The observed difference between the result from the optical and the near-IR lines might conceivably arise from errors in the calibration of the measurements into energy units, or in the correction for interstellar extinction. But in either case the H I relative line strengths between the Balmer and the Paschen lines would not agree as well as they do (Tables 5 and 6 in OTV); nor would the intensities of the H e lines (Table 9 in OTV). Regarding the theoretical uncertainties, we estimate that the uncertainties in the new collision strengths, for the transitions among the low-lying levels under consideration, should not exceed 30\% (Zhang & Pradhan 1994). Also, the errors in transition probabilities should also be equally small, but are immaterial since all of the observed line ratios at N_e = 4000 cm\(^{-3}\) are very close to the low-density limit.

The optical [Fe ii] lines allow us to explore the higher density regime directly for the first time. In Figures 2a and 2b we present two of the most sensitive line ratios, I(5262)/I(8617) and I(5334)/I(8892), as functions of electron density at T = 7000, 9000, and 12,000 K. The observed intensity ratios as given by OTV are also shown. Similar results are obtained for other pairs of the observed and computed optical and IR line ratios, with a total dispersion in the density range derived from all line ratios between N_e = \times 10^3 \text{ cm}^{-3}. The detailed comparisons thus indicate much higher densities for both the optical and the near-IR [Fe ii] line-formation regions than previous studies primarily based on ionic species of elements lighter than iron.

We further investigate the sensitivity of the line intensities in the high-density regime by computing the fractional abundance ratio N(Fe^+)/N(H^+) derived from all observed lines, and examine the dispersion. This approach is equivalent to analyzing all possible line ratios that can be calculated between the eight observed lines. The [Fe ii] line intensities were measured by OTV relative to H I lines; we assume case C recombination to determine the relative intensities of Hα and Hβ (Hummer & Storey 1987). The fractional abundances of Fe^+ derived from the observed lines are presented in Table 1 for T = 9000 K and N_e = \times 10^3 \text{ cm}^{-3} (A), N_e = \times 10^5 \text{ cm}^{-3} (B), N_e = \times 10^6 \text{ cm}^{-3} (C), and N_e = \times 10^7 \text{ cm}^{-3} (D). The scatter in the fractional abun-

### TABLE 2

<table>
<thead>
<tr>
<th>( \lambda ) (Å)</th>
<th>TRANSITION</th>
<th>( N_e = 4000 \text{ cm}^{-3} )</th>
<th>( N_e = 10^6 \text{ cm}^{-3} )</th>
<th>I (OBSERVED)</th>
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<tr>
<td>12567</td>
<td>a^6D_{5/2-} a^5D_{7/2}</td>
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<td>1.00</td>
<td>1.0</td>
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<td>0.13</td>
<td>0.3 ± 0.3</td>
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<tr>
<td>12941</td>
<td>a^6D_{1/2-} a^5D_{3/2}</td>
<td>0.09</td>
<td>0.27</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>13278</td>
<td>a^6D_{3/2-} a^5D_{5/2}</td>
<td>0.06</td>
<td>0.16</td>
<td>0.5 ± 0.3</td>
</tr>
</tbody>
</table>

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dances corresponding to each set, defined as \( \sigma_{\chi} \), is also given. At the given temperature of 9000 K we obtain the best fit for \( N_e = 10^4 \, \text{cm}^{-3} \). A slightly better fit to all the observed lines is obtained in column E with \( N_e = 10^5 \, \text{cm}^{-3} \), indicative of the prevalent density and temperature regime in the observed [Fe II] emitting regions based on the present analysis, which also appears to rule out densities much greater than \( 10^6 \, \text{cm}^{-3} \). It should be noted that the fractional abundances presented in Table 1 establish the consistency and the goodness of fit obtained for different physical conditions, but may not reflect the actual relative abundances of Fe\(^{+}\) in the nebula.

In general higher densities are expected to lead to stronger emission lines. An independent confirmation of the present results, which are based on OTV's [Fe II] measurements, should be possible from previous observations. Such evidence is provided by the work of Lowe, Moorhead, & Gehrels (1979) who measured [Fe II] lines in the near-IR region within a circular aperture of 2' diameter centered on \( \theta^1 \) Ori C. Although their observational uncertainties are large, the measured intensity ratios appear to be inconsistent with those predicted for low electron densities \( N_e \approx 10^4 \, \text{cm}^{-3} \). In Table 2 we compare the relative intensities reported by Lowe et al. with the predicted intensities for \( N_e = 4000 \, \text{cm}^{-3} \) and \( N_e = 10^6 \, \text{cm}^{-3} \), at 9000 K. It is apparent from Table 2 that if the electron density in the [Fe II] emitting region were about 4000 cm\(^{-3} \), all the line intensities except that of \( \lambda 12567 \) would be extremely weak and probably undetectable. On the other hand, with the much higher density shown, the predicted line strengths agree with the measurements within the stated uncertainties. The [Fe II] observations of Lowe et al. are therefore understandable under the assumption of the high-density regions.

4. CONCLUSION

The observed [Fe II] lines are probably emitted very close to the ionization front, where Fe is largely Fe\(^{+}\) and H is largely H\(^-\). Fe\(^{+}\) has a lower ionization potential (16.2 eV) than S\(^+\) (23.3 eV) or O\(^+\) (35.1 eV), and thus is enhanced with respect to these ions in the densest and most shielded (from ionizing radiation) regions near the front. Hence, the higher density regions are favored in the observed [Fe II] emission because of ionization, critical density, and shielding. It is unlikely that these lines arise in the partly ionized globules, for the measurements reported by OTV refer to a fairly smooth region of high surface brightness northeast of the Trapezium, which does not include any of the compact sources, proplyds, or other small bright features (O'Dell et al. 1993; Felli et al. 1993). The larger circular area observed by Lowe et al. (1979) does contain many of these features, but they do not appear to show in the [Fe II] \( \lambda 1.644\) maps published by Allen & Burton (1993). This agrees with the conclusion of Felli et al. (1993) that only a small amount of the total free-free emission comes from the densest compact sources. Hence it appears most likely that the [Fe II] observed in the optical and near-infrared arises chiefly in the denser parts of the ionization front at the edge of the H II region.

The weak observed [Fe II] lines in the Orion Nebula, as reported by OTV provide us with the first spectroscopic indication of high-density regions (\( N_e \approx 10^6 \, \text{cm}^{-3} \)) in the nebula. Such structures were expected to exist but their presence could not previously be established conclusively owing to the lack of accurate atomic data. A more precise determination of the temperature and density conditions in the emission region will require more observational studies of the optical and IR emission-line spectra of the Orion Nebula.

The calculated line intensities and ratios were found to have converged as a function of the number of Fe II levels included. For example, the level populations of first 13 levels differ by no more than 2% between the 16 and the 35 level models; in the 16 level model the last three level populations are higher by about 15%, but the observed line ratios are unaffected. The level populations from the 35 level and the 142 level CR models agree to within 2%.

A related issue is the determination of iron abundance in the Orion Nebula. Current work in progress includes analysis of [Fe III] IR spectral lines (R. Pogge 1994, private communication), which together with the [Fe II] data should yield valuable information not only on the temperature-density structures but also the fractional and total abundance of iron.

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