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IONIZATION STRUCTURE AND SPECTRA OF IRON IN GASEOUS NEBULAE AND PARTIALLY IONIZED ZONES

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RESUMEN

El espectro de emisión y la estructura the ionización de los estados más bajos de ionización del hierro, Fe I-IV, en nebulosas gaseosas son estudiados. Este trabajo incluye: (1) nuevos datos atómicos; (2) el estudio de los mecanismos de excitación de [Fe II], [Fe III] y [Fe IV], y análisis de espectros; (3) el estudio de la estructura y cinemática de las nebulosas. Se muestra que la emisión de [Fe II] de Orión es producida predominantemente por colisiones electrónicas en zonas densas parcialmente ionizadas; la excitación por fluorescencia es mucho menos importante. Hay evidencia adicional sobre las zonas densas que proviene de líneas de [O I] y [Ni II], y también de velocidades medidas de varios iones en la nebulosa. La estructura de ionización del hierro en Orión que resulta del uso de los datos atómicos nuevos, es significativamente diferente a la estructura obtenida en modelos previos. El modelo actual sugiere la existencia de una región predominantemente ionizada con densidades del orden de 10^3 cm^{-3} y una región dinámica parcialmente ionizada con densidades de $10^5 - 10^7$ cm^{-3}. Los modelos de fotoionización también indican que la emisión en la región visual de [O I] y [Fe II] se origina en regiones densas.

ABSTRACT

The emission spectra and the ionization structure of the low ionization stages of iron, Fe I-IV, in gaseous nebulae are studied. This work includes: (1) new atomic data; (2) study of excitation mechanisms for the [Fe II], [Fe III], and [Fe IV] emission, and spectroscopic analysis of observed spectra; (3) study of the physical structure and kinematics of the nebulae. It is shown that the [Fe II] emission from the Orion nebula is predominantly excited via electron collisions in high density partially ionized zones; fluorescence is much less effective. Further evidence for high density zones is derived from the [O I] and [Ni II] lines, and from the kinematic measurements of ionic species in the nebula. The ionization structure of iron in Orion is modeled in the light of the new atomic data, showing some significant differences from previous models. The new model suggests a fully ionized region at densities of the order of 10^3 cm^{-3}, and a dynamic partially ionized region at densities of $10^5 - 10^7$ cm^{-3}. Photoionization models also indicate that the optical [O I] and [Fe II] emission originates in high density partially ionized regions within ionization fronts.

Key words: **ATOMIC PROCESSES — H II REGIONS — ISM: ABUNDANCES — ISM: INDIVIDUAL OBJECTS (ORION NEBULA) — ISM: STRUCTURE — STARS: FORMATION**

1. INTRODUCTION

The spectra and ionization structure of iron are valuable indicators of the physical conditions of ionized nebulae as the several ionization stages of this element span from the cool neutral regions and partially ionized zones, to the fully ionized regions close to the ionizing source.

In earlier works we found that the optical [Fe II] emission in Orion is collisionaly excited in partially ionized zones (PIZs) with high electron densities of $\sim 10^5 - 10^7$ cm^{-3} (Bautista, Peng, & Pradhan 1996; and references therein). In contrast, Baldwin et al. (1996) modeled the optical [Fe II] emission from Orion and suggested that UV fluorescence including self-shielding of UV lines that dominate the photoexcitation is a viable mechanism for the excitation of the [Fe II] lines as opposed to the high electron densities deduced by Bautista et al. The collisional and fluorescent excitation, including optical depth effects, are further investigated herein.

The so called "champagne" model for diffuse nebulae predicts a stratification of velocities and ionization states of emitting ions in the H II region. This correlation between expansion velocities and the physical conditions in nebulae and their ionization fronts is discussed in § 3. Further, the effects of the ionization front on the predicted spectra of neutral and low ionization species, e.g., O I and Fe II, are illustrated.

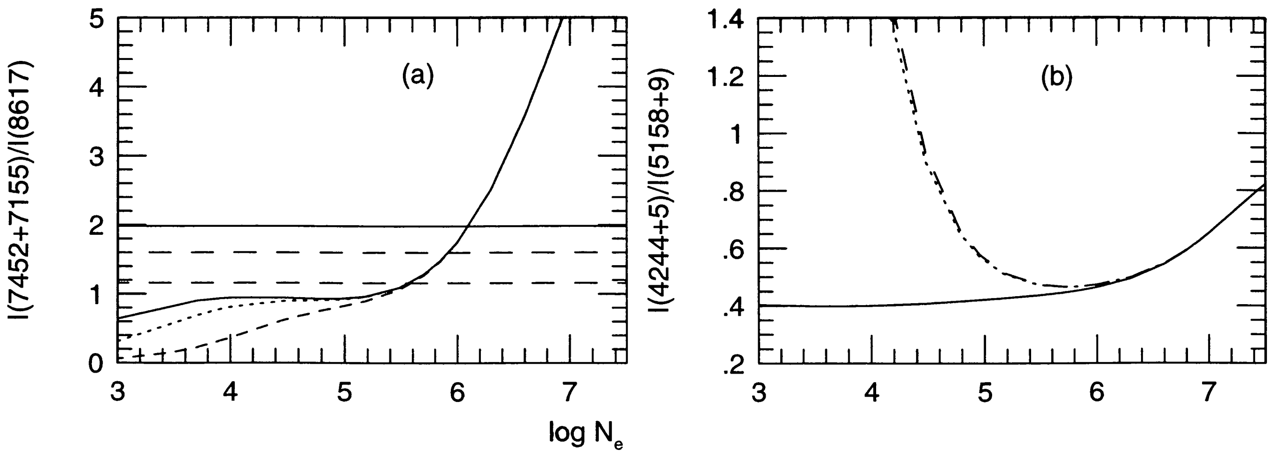

Fig. 1. [Fe II] line ratios vs. log N_e (cm^{-3}) for $T_e = 9000$ K. The curves represent collisional excitation (solid), collisional and fluorescent excitation (dotted), collisional and fluorescent excitation including line self-shielding (long dashed), and collisional and fluorescent excitation for a UV field ten times that in Orion (short dashed). The calculated ratios by Baldwin et al. (1996) are indicated by square dots. The horizontal lines indicate the observed values by Osterbrock, Tran, & Veilleux (1992; solid), Greve, Castles, & McKeith (1994; dotted lines), and Rodríguez (1996; dashed lines).

2. NEW ATOMIC DATA FOR FE I-V

Most of the atomic data for the present work have been calculated by the Ohio State group as part of the Iron Project (Hummer et al. 1993) and the Opacity Project (Seaton et al. 1994). The total electron-ion recombination rate coefficients were calculated using a new unified method, including both the radiative and the di-electronic recombination processes, developed by Nahar & Pradhan (1995). More information about these data can be obtained by request from the authors or from the Web site: http://www-astronomy.mps.ohio-state.edy/ pradhan/ .

3. ANALYSIS OF IRON EMISSION SPECTRA

3.1. The Optical [Fe II] Lines

We have constructed a 159-level CR model for Fe II with collision strengths from Zhang & Pradhan (1995) and Bautista & Pradhan (1996), and radiative transition probabilities from Nussbaumer & Storey (1988), Garstang (1962), Giridar & Ferro (1995), and Nahar (1995). Optical depth effects are also included using the escape probability approximation.

Present results essentially confirm the previous work by Bautista et al. (1996) that the optical, and optical to near-IR, [Fe II] line ratios indicate high densities, $10^5 - 10^7$ cm^{-3}, in the emitting region. That is the case in particular for line ratios that are insensitive to fluorescence, such as those between the 8892 and 8617 Å lines and lines from doublets levels, e.g., 7155 and 7475 Å lines that arise from the $a\ ^2G_{9/2}$ state, which are uncoupled from the ground state. Further, fluorescent excitation of optical lines cannot reproduce the observed spectra, as illustrated in Figure 1. We also find that optical depth effects on the UV lines have negligible effects on the fluorescent excitation of the optical [Fe II] lines in Orion, contrary to the conclusions of Baldwin et al. (1996).

3.2. Analysis of [Fe III] and [Fe IV] Lines

We use a 34-level CR model for Fe III using atomic data from Zhang (1996) and Nahar & Pradhan (1996). The observed [Fe III] line ratios indicate densities in agreement with with diagnostics using other lines of other species, such as [S II], that indicate densities of a few times 10^3 to almost 10^4 cm^{-3}.

We use a 33-level CR model of Fe IV with collision strengths of Zhang & Pradhan (1997) and A-values

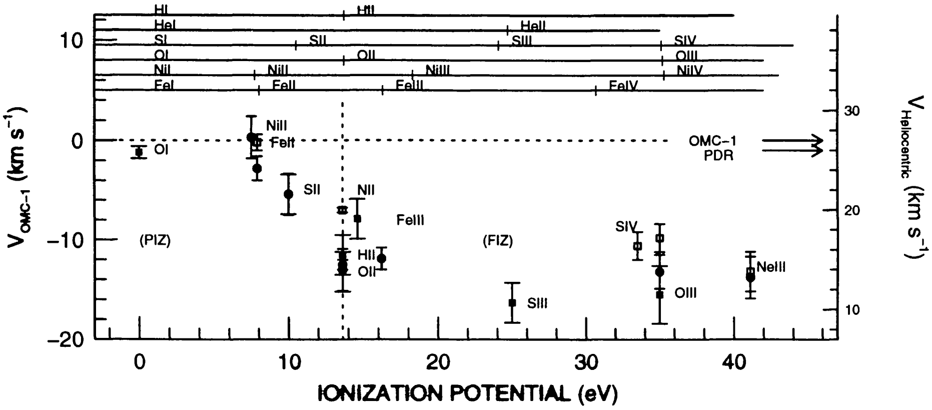

Fig. 2. Observed velocities of optical lines in Orion vs. the photon energy required to produce the ion specie. The velocities of the molecular cloud (OMC-1) and the photodissociation region (PDR) are also indicated. The observations are from Kaler (1967; empty squares), Fehrenbach (1977; filled circles), and O'Dell & Wen (1992; filled squares).

from Garstang (1958). For conditions of $N_e = 4000$ cm^{-3} and $T_e = 9000$ K the strongest predicted lines lie in the UV, e.g., 2835.7 Å($^6S_{5/2} -^4 P_{5/2}$), 2829.4 Å($^6S_{5/2} -^4 P_{3/2}$), 2567.6 Å($^6S_{5/2} -^4 D_{5/2}$).

In the optical the strongest predicted features are 4906.6 Å($^4G_{11/2} -^4 F_{9/2}$), 4900.0 Å($^4G_{9/2} -^4 F_{7/2}$), and 4903.1 Å($^4G_{7/2} -^4 F_{7/2}$). The strength of the 4906.6 Å line with respect to the nearby [Fe III] 4881 Å line is computed to be $0.012 \times N(Fe^{3+})/N(Fe^{2+})$.

4. KINEMATIC ANALYSIS OF THE ORION NEBULA

Figure 2 shows the observed velocities of optical lines in Orion vs. the minimum photon energy required to produce the ionized species (adapted from Kaler 1967 and Balick, Gammon, & Hjellming 1974). A sharp change in velocity is observed between ions that require photon energies greater than 13.6 eV (1 Ry) and neutrals with low first ionization potential ions, like O^0 and Fe^+. It is also clear that forbidden emission from [O I], [Fe II], and [Ni II] is likely to originate primarily from the same zone at the ionization front.

In a frame of reference co-moving with the ionization front $\rho v = constant$. This establishes a lower limit to the density of the [O I], [Fe II], [Ni II] emitting region, according to the uncertainties of the measured velocities, of at least an order of magnitude greater than the density of the fully ionized zone.

5. IONIZATION STRUCTURE OF IRON IN ORION

The main source of uncertainty in calculating the ionization structure lies in the assumed structure for the cloud (constant density, exponential or power law density with radius, constant gas pressure, constant gas and radiative pressure, etc.). Another difficulty is the poor understanding of ionization fronts which are known to be dynamic.

Table 1 reveals the difficulty of reproducing the observed spectra for all the stages of oxygen simultaneously. Model (I) uses constant gas pressure conditions with a mean density of $\sim 10^4$ cm^{-3}, comparable to those of Baldwin et al. (1996). These models systematically overestimate the intensity of [O II] and [O III] by up to a factor of two while the [O I] emission is underestimated by up to a factor of three. Models (II) and (III) were calculated with constant gas pressure conditions and a mean density of ~ 4000 cm^{-3}, but with stellar fluxes from Kurucz (1979) and a NLTE flux from Sellmaier et al. (1996) respectively. These models reproduce well the spectra of [O II] and [O III]. However, the discrepancies for the [O I] lines increase to about a factor of five. The same conditions as in model (III) were used for model (IV), except that a high density ionization front was added with 10^6 cm^{-3} at a depth in the cloud of 0.21 pc. Here, [O I] lines are considerably enhanced, close to the observed levels, as a result of the contribution from the partially ionized zone within the front.

TABLE 1

OPTICAL SPECTRUM OF OXYGEN IN ORION VS. PHOTOIONIZATION MODELS.

Ion	line (Å)	Observed/I(Hβ) × 100		Baldwin et al. (1996; B96)			Present			
		B96	OTV	(A)	(B)	(C)	(I)	(II)	(III)	(IV)
[OI]	6300	0.959	0.722	0.341	0.336	0.699	0.34	0.20	0.17	0.75
	5577	0.058	< 0.0136	0.0044	0.0043	0.0095	0.004	0.002	0.002	0.006
[OII]	3727	146	94	188	188	149	186	209	145	126
	7320	6.21	...	...	...	...	13.8	7.86	4.44	11.6
[OIII]	4363	1.39	...	...	...	1.93	2.39	0.74	0.69	...
	5007	302	343	465	460	379	395	507	263	228

6. CONCLUSIONS

The [Fe II] emission from H II regions like Orion is shown to originate primarily from high density partially ionized zones (PIZ's) within the ionization front. This conclusion is derived from a number of density line ratio diagnostics, including ones that are insensitive to fluorescent excitation by the UV radiation field.

The observed kinematics of the Orion nebulae seem to be well correlated with the physical conditions. Moreover, the expansion velocities of optical emission from O^0, Fe^+, and Ni^+ are remarkably similar to those of the PDR and the molecular core, providing further evidence for the PIZ's.

Photoionization modeling of Orion also indicate that high densities are required at the ionization front to explain the observed [O I] and [Fe II] emission.

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