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Final Report

This document comprises the final report for our IUE grant NAG 5-710 entitled, "Model of the Orion Nebula Incorporating IUE Data".

I. Introduction

Our research basically has been directed along two avenues. First of all, we have a long-standing interest in modeling H II regions in order to understand the physical processes involved and to extract important astrophysical information. This includes knowledge of chemical elemental abundances and properties of the exciting stars, such as their far ultraviolet spectrum. The Orion Nebula is a prime candidate to study because it is nearby, bright, the extinction is not large, and its appearance is reasonably circular (e.g. Gordon et al. 1986). Such a shape is consistent with a geometrical structure that is spherically symmetric (1-D) or one that is axisymmetric (2-D) seen nearly face-on. Previously all detailed modeling of the ionization and thermal structure of H II regions has been confined to 1-D because of computational complexity. We now have the capability to treat the 2-D case with much of the level of physical sophistication as the 1-D case (Rubin 1984). The interpretation of the spectra of gaseous nebulae in terms of underlying physical processes requires measurements of line intensities at different points in the object and over as wide a set of excitation and ionization conditions as practical. Observations of nebulae have been made for many years in the optical and radio but only recently in the infrared and ultraviolet. These relatively new windows allow observations of lines of ionization states not available in the radio or optical--providing a much more complete set of known quantities to undertake a meaningful modeling effort.

Whereas the first avenue of approach is a detailed study of the Orion Nebula, the second interest is to improve in general the determination of chemical elemental abundances in H II regions. In view of recent observational advances, in particular the availability of IR and UV lines, improved atomic data, and an improved knowledge of important physical processes, a reexamination of nebular abundances should be timely. Reliable values for quantities such as O/H, C/O, N/O in the interstellar medium are of utmost importance in understanding galactic chemical evolution.

II. Studies of the Orion Nebula

Since the last spherical modeling of the Orion Nebula (Simpson 1973), there have been numerous advances in virtually every aspect that contributes to solving the problem. As mentioned earlier IR and UV observations permit measurements of lines of species that have no optical forbidden lines.

These include transitions in the IR of C II at 158 μm, N III at 57 μm, Ne II at 12.8 μm, S IV at 10.5 μm, and Ar II at 6.99 μm and in the UV, C III 1906, 1909 Å as well as C II 2326 Å. The last line is really the primary probe of C II in the H II region since the bulk of C II 158 μm will generally occur outside the H^+ region. Our group (Erickson et al. 1986) has been active using the Kuiper Airborne Observatory (KAO) to obtain new observations of several of these IR lines in Orion and other nebulae. We have attempted in our IUE proposal to obtain the UV line data from archival material.

Before proceeding with the more difficult 2-D modeling described above, we fealt it was important to try to fit the available data for Orion with a spherical model. This paper will appear shortly (Simpson et al. 1986). However from dynamical considerations it is known that the Orion Nebula is probably a "blister" geometry object (Zuckerman 1973). The H II region is in the foreground of the large Orion Molecular Cloud (OMC1). This geometry/density distribution is having more success at matching the intensities of lines of singly ionized species, which were in general significantly underestimated by the spherical models. Progress on this ongoing work is listed below.

1) Rubin (1985) gave a review paper at the Model Nebulae Workshop in Paris 8-19 July, 1985 that incorporated work on the Orion Nebula.

2) Rubin et al. (1987) presented a paper at the IAU Symposium on Star Forming Regions in Tokyo 11-15 November, 1985 entitled Non-Spherical Models of the Orion Nebula and M17. Details of that meeting were in the trip report of 10 February, 1986. On 25 November, 1985 Rubin gave a paper at the IAU General Assembly in New Delhi on the N/O Abundance Ratio in Gaseous Nebulae (including Orion). These papers have not yet used the IUE observations directly but have been very much influenced by our concomitant IUE theoretical work.

3) Rubin, Simpson, and Haas (1987) will present a paper at the AAS meeting in January, 1987 entitled "A Two-Dimensional Model for the Ionized Gas in the Orion Nebula".

Rubin spent 5 days in December, 1985 at the Goddard IUE data analysis facility beginning the archival work on the Orion spectra. He consulted with Dr. Barry Turnrose on the data processing since much of the useful original observations were made by Turnrose and Dr. Peter Perry. He systematically reprocessed about 40 spectra. We have not yet had the time and money to properly complete the reduction of the archival Orion Nebula data.

III. Studies of the Elemental Abundance Ratios N/O, C/H, and C/O

A major unexpected surprise of this work was that recombination processes may significantly enhance the intensities of some well known lines arising from low-lying metastable levels that have been treated as solely collisionally excited. As a result, under certain conditions which are achievable in real nebulae, including Orion, recombinations can compete with collisional excitation in producing these lines (Rubin 1986). This work serves to bring closer agreement in general for H II regions between the optically determined average of ~ 0.07 (Shaver et al. 1983) and the lowest N/O values from IR lines ~ 0.2 (Lester et al. 1983).

The largest effect is for the [O II] lines, including the 2470 Å line (blended with IUE), one of the strongest and most important emission lines observed by IUE in nebulae. There may also be a recombinational enhancement of C III] 1908 Å in nebulae that are higher excitation such as Planetary Nebulae. The physics has been added to the computer modeling code to predict the intensities of important C and O lines observed by IUE, which are relied upon heavily to determine C/O abundance ratios. In the treatment of [O II] 2470 Å and C III] 1908 Å, recombination terms have been added to the statistical equilibrium calculation. For the C II] 2326 Å lines, there is a considerable revision of the atomic constants used to compute the line intensities. When adding this to the code, we used the recent improvement of Lennon <u>et al.</u> (1985).

Since there have been in addition substantial changes in the relevant atomic data and UV exticition corrections, we rederived C/O and C/H for the Orion Nebula from previous IUE observations. The early low resolution IUE observations of Perinotto and Patriarchi (1980) and Torres-Peimbert et al. (1980) had been properly corrected for the SWP intensity transfer function problem. They were also made in the region close to the Trapezium, unlike the Perry and Turnrose observations, that we are reexamining which were made in the vicinity of the SE bar. The results of our study were presented at the London conference on New Insights in Astrophysics (Rubin and Zuckerman 1986, copy enclosed). We find that C/H is ~ 20-40% lower than the prior analyses. Our C/O results are presented in the paper and are not directly comparable with the earlier papers since the temperature used by Torres-Peimbert et al. (1980) were somewhat higher. The improved treatment does yield substantially more reliable values. Accurate abundance ratios are important for a wide variety of problems including, for example, the fundamental C/O ratio as well as the galactic chemical evolution of the heavy elements.

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ELEMENTAL ABUNDANCE DETERMINATION IN GASEOUS NEBULAE FROM IUE LINES

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ABSTRACT

A method for obtaining the C/O elemental abundance ratio for high excitation H II regions is discussed. This is then applied to rederive C/O for the Orion Nebula from previous IUE observations using improved atomic data and extinction corrections. It is also found that C/H is ~ 20-40% lower than previously determined. When recombinations contribute importantly to [O II] 2470 and 7325 A emission, we caution against use of these lines for assessing the O^+ ionic abundance with the so-called empirical method.

Key words: IUE, Abundances, Orion Nebula

1. INTRODUCTION

Several recent developments make it worthwhile to rederive the C/H and C/O ratio in Orion and other gaseous nebulae. Evaluation of these ratios depends heavily on space ultraviolet transitions. For H II regions and low excitation planetary nebulae, carbon is essentially in two ionization stages -- C II and C III whose abundances are gleaned from the C II] 2326 A lines and C III] 1908 A lines. There have been substantial revisions in the atomic data since the early IUE observations of Orion (Perinotto and Patriarchi 1980 = PP; Torres-Peimbert, Peimbert, and Daltabuit 1980 = TPPD). The most dramatic changes have occurred for the collision strengths and transition probabilities for the C II] 2326 A lines (Lennon et al. 1985). For O^+ abundances derived from [O II] 2470 A, there is an improved A-value (Zeippen 1982).

In addition, Rubin (1986) has shown that there should be a substantial enhancement of the [O II] 2470 A line due to recombinations in the O III region of the Orion Nebula and other nebulae as well. Previously this line (actually two lines) was treated as solely collisionally excited. Working from the framework of our model of Orion (Simpson et al. 1986), we predict I(2470 A) to increase by ~ 150% over the purely collisionally excited value for a line of sight that corresponds to the brightest region (Ori 1 of PP) and the IUE large aperture. Significant enhancements are also expected for other classes of gaseous nebulae. For instance in Rubin (1986) the PN NGC 7662 modeled by Harrington et al. (1982) was "retrofitted" for the O II recombination terms utilizing their fractional ionic abundances and average T_e values appropriate for the relevant ionic species. It was found that the 2470 A integrated flux would increase ~ 50%. Figure 1 illustrates the effect on I(7325)/I(3727). Throughout this paper, I(7325) and I(3727) mean I(7320,30) and I(3726,29). Since the 2470 A and 7325 A multiplets both arise from a common upper ^2P level, a similar plot would result for I(2470)/I(3727).

Therefore, when recombinations are contributing to the intensity of one or more of these O II lines, the empirical method (which assumes collision-only excitation) for obtaining N_e, T_e, and O II abundance is inappropriate. In general, the direct effect of including recombination terms in the statistical equilibrium would be to lower the O abundance somewhat depending on how much O III was present. In addition, there is the possibility that the O III/O II ratio and values of T_e, N_e used for prior analyses might need revision in view of the recombination terms for [O II] affecting intensities of the 7325 A and even 3727 A lines.

Finally, there is a substantially improved Orion extinction curve derived from IUE observations by Bohlin and Savage (1981) that generally indicates less UV extinction than the earlier work of Bless and Savage (1972). In view of the above mentioned effects, we shall reevaluate C/O and C/H for the Orion Nebula using the IUE observations of PP and TPPD.

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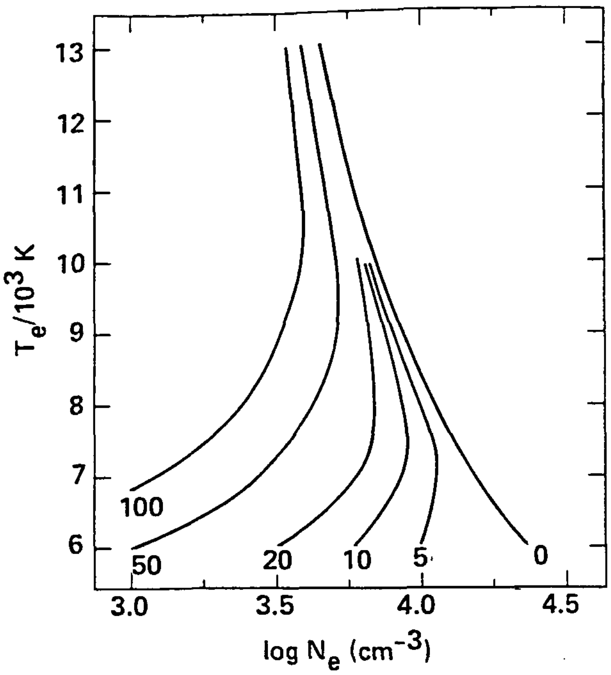

FIGURE 1. We show curves that represent possible solutions for T_e and N_e for an assumed I(7325 Å)/I(3727 Å) = 0.1, close to the value observed near the Trapezium, corrected for absorption. The curves are labeled with different values of the ratio r = $\langle N(O^{++})\rangle / \langle N(O^{+})\rangle$ representing different contributions to the statistical equilibrium due to recombinations. The notation, for example, for the average density, $\langle N(O^{+})\rangle$, means $\int N_e N(O^{+}) dV / \int N_e dV$. For surface brightness corresponding to lines of sight near the Trapezium in the Orion Nebula, our models show the ratio r is ~20.

2. DERIVATION OF C/O AND C/H

Because of the significant contribution to the intensity of 2470 Å in Orion due to recombinations in the O III region, we take a somewhat different approach to the empirical evaluation of C/O. (With a detailed modeling analysis the contributions of both collisional excitation and recombinations could be properly accounted for so that O^{+} lines could be used.) Basically, we assume that for Orion the volumes occupied by O^{++} and C^{++} are the same. Then, N(C)/N(O) ~ $N(C^{++})/N(O^{++})$, particularly along central lines of sight in resolved objects. For lower excitation objects V(C III) > V(O III) (see Rubin 1985) and the method will provide only an upper limit if the volumes are assumed coextensive. The procedure for obtaining C/O and C/H is as follows:

1) The original analyses of PP and TPPD both used the Orion Nebula extinction curve of Bless and Savage (1972) obtained from the Orbiting Astronomical Observatory 2. We employ the much improved average Orion Nebula extinction curve of Bohlin and Savage (1981) to correct the original line fluxes to intrinsic line intensities. In the derivation of f(λ) (see PP or TPPD) from E(λ-V)/E(B-V) (see Bohlin and Savage 1981), we use E(B-V) = 0.32, which is the average for θ^1 Ori A,C,D (Bohlin and Savage 1981). We also use C(Hβ) values given in PP and TPPD.

2) The observations of the [O II] 2470 Å lines are utilized together with those of 7325 Å to place the IUE observations on the same scale as the optical ones. This is done by using the expected multiplet intensity ratio I(2470)/I(7325) = 0.75, which is an updated value from that of Harrington et al. (1980).

3) The C III] 1908 Å and the [O III] 5007 Å lines are used to obtain the C^{++}/O^{++} ratio. For objects where collisional deexcitation of the upper levels of these lines is negligible (valid for Orion),

$$\frac{N(C^{++})}{N(O^{++})} = 0.0658 \exp\left(\frac{4.00\ \mathrm{eV}}{kT_0}\right) \frac{I(1908)}{I(5007)} \quad .$$

Since we are using this method when it is valid to assume that the C III and O III volumes are about the same, the value of T_e is the appropriate average for the C^{++},O^{++} volume. It is important to use the average temperature T_0 given by

$$T_0 = \frac{\int N_e\, N(O^{++},C^{++})\, T_e\, dV}{\int N_e\, N(O^{++},C^{++})\, dV} \quad .$$

4) Abundance ratios are rederived for region Ori 1 uv of TPPD and Ori 1 of PP. Observed areas were chosen to correspond closely with Ori 1a and 2b respectively of Peimbert and Torres-Peimbert (1977). (Because of the different aperture sizes, the optical and UV areas do not agree exactly.) In Table 1 we present the results for average temperatures of 8000 and 8500 K, which correspond to the narrow range found to be self consistent with our detailed spherical modeling. (The temperatures derived in a non-spherical blister model may differ from these.)

5) For the C/H derivation, C II] 2326 Å and C III] 1908 Å provide ionic density information and are used in conjunction with Hβ to obtain N(C)/N(H) = $N(C^{+} + C^{++})/N(H^{+})$. Again calculations are made for two average temperatures of 8000 and 8500 K and utilizing the improved atomic data described earlier. The latter temperature is essentially what both PP and TPPD used for their original analyses. Results are summarized in Table 1.

3. RESULTS AND DISCUSSION

1. Our detailed computer models of the ionization and thermal structure of the Orion Nebula show that for the volumes sampled by the above mentioned observations, the O III and C III emission is coming from the same region. From the models, the appropriate average temperature in this C III, O III region for the lines of sight in question are calculated to be ~ 8000 - 8500 K, using the range of C and O elemental abundances found.

Table 1

Region	Ref.	Location relative to θ^1Ori C	N(C)/N(O) = $N(C^{++})/N(O^{++})$		N(C)/N(H)	
			8000 K	8500 K	8000 K	8500 K
Ori 1 uv	TPPD	45" N	0.97	0.69	3.58(-4)	2.06(-4)
					previously	3.31(-4)*
Ori 1	PP	34" W,3" S	0.88	0.63	3.51(-4)	2.03(-4)
					previously	2.51(-4)#

*TPPD use $\langle T_e \rangle$ = 8700 K for C III and 8500 K for C II.
#PP use $\langle T_e \rangle$ = 8500 K.

2. Recombinations play an important role in contributing to the [O II] 2470 and 7325 A lines in the Orion Nebula and other nebulae. When this is important, the derivation of properties of the plasma -- N_e, T_e, and elemental abundances -- from observations of affected lines will not be appropriate with a collisional-excitation-only treatment.

3. When recombinations are important in the production of the [O II] line emission, the 2470 A line should not be used with the so-called empirical method for assessing O^+ abundances.

4. In light of 3, we find for the Orion Nebula that it is more reliable to determine the C/O ratio from lines of C III and O III.

5. Even though there are some revisions in virtually every aspect of the abundance analysis, the effects are not all in the same direction. The bottom line effect on the C/H ratio is to decrease the value ~20-40% from the prior analyses. However, the improved treatment presently possible does yield significantly more reliable values. The previous C/O ratio obtained by TPPD was 0.79. This was obtained assuming an average temperature of 8700 K for the C III region and 9100 K for the O III region.

6. By using the temperature T_0 in our analysis, it can be demonstrated that if there are temperature fluctuations, the effect would be to lower C/O and C/H.

7. Reliable abundance ratios are important for a wide variety of problems including, for example, the fundamental C/O ratio in the interstellar medium as well as the evolution of heavy element abundances in the galaxy. Langer et al. (1984) have suggested that in the gas phase in molecular clouds, C/O is greater than unity. Since the Orion Nebula was recently a molecular cloud, it is important to constrain accurately its C/O ratio. If C/O is greater than unity in the gas phase in molecular clouds, then our results indicate that relatively more O than C must be hidden (e.g. in dust grains) in these clouds compared to the Orion Nebula. In any event, since main-sequence stars have C/O < 1, there must be more O than C in the interstellar medium as we deduce, at least for the gas phase in Orion.

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