ELECTRON DENSITIES IN THE ORION NEBULA

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ABSTRACT

Measurements of the intensity ratio of the two components of the [O II] λ3727 emission line at various points in the Orion Nebula are given. Since the variation of density in the nebula is indicated by the variation in surface brightness, the measurements are used to test the prediction of Seaton that the intensity ratio should vary with electron density. The conclusion is that the observations fit the theory well. The densities derived range from a high of $3 \times 10^4$ electrons/cm$^3$ at a point near the Trapezium to a low of $3 \times 10^2$ electrons/cm$^3$ at some of the faintest points observed in this investigation.

I. INTRODUCTION

Seaton (1954a) has recently calculated the intensity ratio of the two components of the [O II] λ3727 emission line as a function of electron density. Therefore, the measurement of this intensity ratio in a nebula, together with the use of his theoretical calculation, immediately gives the electron density in that nebula. This is a very simple and powerful method for determining the density in emission objects and will have wide application. However, the method is new, and the theoretical calculation of the variation of the intensity ratio with electron density should be checked in any way possible.

The present paper is concerned with such a check, made by observing the λ3727 intensity ratio at many points in the Orion Nebula. It is well known that in this nebula there is a very steep decrease of surface brightness from the Trapezium outward, and it is therefore quite clear that the density falls sharply outward. Thus, although the absolute densities are not known, the qualitative run of densities is known, and therefore the way in which the intensity ratio should change going outward is known. Besides this check, a calculation is made of the electron densities at various points in the nebula for which there are observed values of the λ3727 intensity ratio.

II. THEORY

The [O II] line λ3727 consists of the two components λ3726.05 and λ3728.80 (Bowen 1955), arising from transitions from the upper $^4D_{5/2}$ and $^4D_{3/2}$ states, respectively, to the ground $^4S_{3/2}$ state. In emission nebulae the O II ions are excited from the ground state to the upper states by collisions with electrons, and so the excitation conditions and therefore the ratio of intensities of the two components depend on the electron density. At very low densities the time between collisions is very long, and every ion that reaches an excited state by a collision is almost certain to lose its energy by radiating a photon before it has another collision. Under these circumstances the ratio of intensities of the two components is proportional to the ratio of excitation cross-sections and is λ3729/λ3726 = 1.5. (This fractional symbol will be used throughout the present paper to mean the ratio of the intensity of λ3728.80 to the intensity of λ3726.05.) On the other hand, at very high densities the time between collisions is very short, and an ion enters and leaves the excited state by collisions many times before it radiates a photon. Under these circumstances the ratio of intensities of the two components is the same as in thermodynamic equilibrium and is λ3729/λ3726 = 0.47. At intermediate
densities the intensity ratio varies between these limits. The detailed form of the variation, according to Seaton (1954a), is

$$\frac{\lambda 3729}{\lambda 3726} = 1.5 \frac{1 + 3.3x}{1 + 10.5x'}$$

where $x = 10^{-2}N_e/T^{1/2}$, in terms of the electron density $N_e$ and temperature $T$.

The foregoing expression was derived by using numerical values of the transition probabilities computed by Garstang (1952) and a numerical value of the $^{3}S-^{3}D$ excitation cross-section computed by Seaton (1953). The cross-section for the $^{3}D_{5/2}-^{3}D_{3/2}$ process, which also enters the formula for the intensity ratio, was not computed, but instead an estimated value was used. An improved value of this cross-section may be expected to alter somewhat the relation between intensity ratio and electron density but will not change its general form.

Fig. 1. Variation of $\lambda 3729/\lambda 3726$ intensity ratio with electron temperature at 10,000° K

A conventional value of the temperature of 10,000° will be used in the present paper for computing densities from intensity ratios by expression (1). The theoretical calculations summarized by Spitzer (1954) show that the temperature in an $H\alpha$ region must be in the general neighborhood of this value. In addition, there is a determination of the temperature in the Orion Nebula from a comparison of the intensities of the $[O III]$ nebular and auroral lines. This calculation was first made by Aller (1946), who obtained a value of 10,500° by using the older computations of the excitation cross-sections; it was repeated by Seaton (1954b), who, attempting a correction for interstellar obscuration and using the newer values of the cross-sections, obtained a value of 13,000°. Both authors used the intensity measures of Wyse (1942), which refer to a bright region near the Trapezium. Thus the use of a value of 10,000° for the temperature seems safe, particularly as the percentage error in the electron density is only half the percentage error in the temperature.

Figure 1 shows the variation of the $\lambda 3729/\lambda 3726$ intensity ratio with electron density, calculated from equation (1) with an assumed temperature of 10,000°. According to this curve, the intensity ratio should be the smallest, but not less than 0.47, in the central, brightest, densest regions of the Orion Nebula and should increase in the outer, fainter, less dense regions, but not to a value greater than 1.5.
The previous photometric work on the $\lambda 3729/\lambda 3726$ intensity ratio was done by Aller, Ufford, and Van Vleck (1949). They observed a number of bright planetary nebulæ, which are relatively high-density objects, and the $\lambda 3729/\lambda 3727$ intensity ratios clustered near 0.5, in agreement with the theoretical expectation. The intensity ratios measured for the two objects, NGC 40 and IC 4593 were 0.84 and 0.67, respectively, significantly larger than the mean; these objects, as Aller et al. (1949) pointed out, are two of the three objects of lowest surface brightness (and hence statistically of lowest density) in their list.

No observations of the $[O \Pi] \lambda 3729/\lambda 3726$ intensity ratio larger than 0.84 have previously been published. However, $S \Pi$ has an electronic structure similar to that of $O \Pi$, except that the sulphur ion has one more closed shell, and Seaton's (1954a) calculations predict that the intensity ratio of the red $[S \Pi]$ lines $\lambda 6717$ and $\lambda 6731$ changes with density in a fashion similar to that of the intensity ratio of the $[O \Pi]$ lines $\lambda 3729$ and $\lambda 3726$. Published data show this effect in $S \Pi$, for in bright planeraries, which are relatively high-density objects, $\lambda 6731$, analogous to $\lambda 3726$ of $O \Pi$, is stronger (Wyse 1942), while in $H \Pi$ regions, which are relatively low-density objects, $\lambda 6717$, analogous to $\lambda 3729$ of $O \Pi$, is stronger (Johnson 1953).

III. OBSERVATIONS

The observations of the present paper were made with the Newtonian-focus spectrograph of the 100-inch telescope. The plates were taken in the fifth-order ultraviolet with an $F/1.5$ camera, giving a dispersion of approximately 66 A/mm at $\lambda 3727$. The slit was opened so that its projected width on the plate corresponded to about 1.8 A, in order to make the line profile as flat-topped as possible. All the exposures were taken on Kodak IIa-O plates, with exposure times ranging from 50 seconds to 90 minutes.

The photometric calibration was provided by step-strip plates, taken with the calibration optics of the 100-inch telescope coudé spectrograph. Each calibration plate was taken from the same box as the nebular plate with which it was used, exposed for a time not different by more than a factor of 3 from the exposure time of the nebular plate, and developed with it. The plates were traced with the recording microphotometer of the California Institute of Technology at a magnification of either nine hundred or eighteen hundred times. The peak intensities of the two components were measured to get the $\lambda 3729/\lambda 3726$ intensity ratios. Tracings of comparison lines and also calculations according to the formula of van Cittert (Unsold 1938) agreed in showing that the intensity of one component at this point is not appreciably affected by the wing of the other component.

Observations were made at the sixteen points identified in Table 1. In this table the first column gives the letter identifying the point; the second column gives a reference star; the third and fourth columns give the co-ordinates of the center of the slit in minutes of arc, measured north and east, respectively, from this star; and the fifth column gives the position angle of the slit. These slit positions are shown marked on three different direct exposures of the Orion Nebula in Figure 2. The slit length was 3 mm or 48" in all cases, but at points $A$, $B$, $D$, and $F$ the structure of the nebula is so patchy that a length of only about 20" was measured on the plate. At points $T$, $V$, $W$, $X$, and $Y$ the slit was trailed back and forth over a length of about 90" during the exposure, and the measured value of the $\lambda 3729/\lambda 3726$ ratio refers to an average value over this length, while at the other points the slit was held fixed with respect to the nebula.

The sixth column of Table 1 gives the mean value of the measured $\lambda 3729/\lambda 3726$ ratio for each point; the seventh column gives the average deviation, without regard to sign, of a single plate from this mean; and the eight column gives the number of plates measured. Finally, the last column gives the approximate distance of the point from the center of the Trapezium.
IV. INTERPRETATION

Table 1 shows that there is good correlation of the $\lambda 3729/\lambda 3726$ intensity ratio with distance from the Trapezium, and a comparison of Table 1 and Figure 2 shows that this is at the same time a correlation of the intensity ratio with surface brightness. The smallest $\lambda 3729/\lambda 3726$ intensity ratio measured is 0.50, a little larger than the theoretical lower limit of 0.47, while the largest ratios measured are 1.24 and 1.26, well below the upper limit of 1.50. Point $P$ deviates from the relationship between $\lambda 3729/\lambda 3726$ and surface brightness; but this is obviously due to the fact that it is in a region of extremely heavy absorption. Point $Z$ has an intensity ratio somewhat smaller than either its surface brightness or its distance from the Trapezium would suggest; it is a point along the front which bounds NGC 1976 to the north and which may thus be a thin region of higher density.

**TABLE 1**

<table>
<thead>
<tr>
<th>Point</th>
<th>Reference Star</th>
<th>Slit</th>
<th>P.A.</th>
<th>$\lambda 3729/\lambda 3726$</th>
<th>A.D.</th>
<th>n</th>
<th>Distance from Trapezium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$\theta_1$ Ori B</td>
<td>-0.5</td>
<td>140°7</td>
<td>0.50</td>
<td>0.02</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>$B$</td>
<td>$\theta_1$ Ori A</td>
<td>+0.5</td>
<td>90°0</td>
<td>0.61</td>
<td>0.03</td>
<td>3</td>
<td>1.9</td>
</tr>
<tr>
<td>$D$</td>
<td>$-5^\circ1318$</td>
<td>+0.4</td>
<td>90°0</td>
<td>0.77</td>
<td>0.02</td>
<td>3</td>
<td>2.6</td>
</tr>
<tr>
<td>$F$</td>
<td>$-5^\circ1318$</td>
<td>+0.1</td>
<td>90°0</td>
<td>0.76</td>
<td>0.04</td>
<td>2</td>
<td>2.6</td>
</tr>
<tr>
<td>$H$</td>
<td>Bond 335</td>
<td>+0.1</td>
<td>90°0</td>
<td>1.24</td>
<td>0.03</td>
<td>3</td>
<td>14.0</td>
</tr>
<tr>
<td>$J$</td>
<td>Bond 449</td>
<td>-0.4</td>
<td>90°0</td>
<td>1.17</td>
<td>0.00</td>
<td>3</td>
<td>9.3</td>
</tr>
<tr>
<td>$K$</td>
<td>Bond 363</td>
<td>+3.0</td>
<td>90°0</td>
<td>1.05</td>
<td>0.03</td>
<td>3</td>
<td>13.5</td>
</tr>
<tr>
<td>$M$</td>
<td>Bond 335</td>
<td>-2.4</td>
<td>90°0</td>
<td>1.26</td>
<td>0.05</td>
<td>3</td>
<td>16.3</td>
</tr>
<tr>
<td>$P$</td>
<td>$-5^\circ1326$</td>
<td>+2.9</td>
<td>90°0</td>
<td>0.92</td>
<td>0.02</td>
<td>2</td>
<td>3.3</td>
</tr>
<tr>
<td>$R$</td>
<td>$-5^\circ1325$</td>
<td>-0.3</td>
<td>90°0</td>
<td>0.96</td>
<td>0.02</td>
<td>2</td>
<td>7.6</td>
</tr>
<tr>
<td>$T$</td>
<td>$-5^\circ1326$</td>
<td>+1.2</td>
<td>90°0</td>
<td>0.90</td>
<td>0.02</td>
<td>2</td>
<td>3.5</td>
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<tr>
<td>$V$</td>
<td>$\theta_1$ Ori A</td>
<td>+1.1</td>
<td>90°0</td>
<td>0.64</td>
<td>0.02</td>
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<tr>
<td>$W$</td>
<td>$\theta_1$ Ori B</td>
<td>-0.4</td>
<td>90°0</td>
<td>0.55</td>
<td>0.02</td>
<td>2</td>
<td>0.7</td>
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<tr>
<td>$X$</td>
<td>$\theta_1$ Ori B</td>
<td>+0.5</td>
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<td>0.58</td>
<td>0.00</td>
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<td>1.0</td>
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<tr>
<td>$Y$</td>
<td>Bond 635</td>
<td>+0.4</td>
<td>90°0</td>
<td>0.74</td>
<td>0.00</td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>$Z$</td>
<td>Bond 423</td>
<td>-2.3</td>
<td>90°0</td>
<td>0.96</td>
<td>0.03</td>
<td>3</td>
<td>14.2</td>
</tr>
</tbody>
</table>

The highest density found from these $\lambda 3729/\lambda 3726$ ratios is a value of approximately $3 \times 10^4$ electrons/cm$^3$ at point $A$. Strömgren (1951) has determined a density of between $10^3$ and $10^4$ hydrogen atoms/cm$^3$ at the center of the Orion Nebula by measuring the absolute intensity of $H\beta$. His measurement refers to an average over a diameter of 1.3 and thus is probably roughly comparable with the point $W$, for which the density of $1 \times 10^4$ electrons/cm$^3$ is found in the present investigation. The lowest density found from the $\lambda 3729/\lambda 3726$ ratios in the Orion Nebula is approximately $3 \times 10^2$ electrons/cm$^3$ at points $H$ and $M$. It should not be concluded from Table 1 that the $\lambda 3729/\lambda 3726$ ratio does not become larger than 1.26; the outermost, faintest, least dense parts of the Orion Nebula were not observed in the present investigation. On the contrary, observations to be reported in detail later show the $\lambda 3729/\lambda 3726$ intensity ratios in $H\pi$ regions such as NGC 281 and NGC 7000 to be much closer to the theoretical low-density limit of 1.50.

The conclusion may be drawn that the observations of the $\lambda 3729/\lambda 3726$ intensity ratio in the Orion Nebula fit the theory of Seaton (1954a) well. The densities derived
Fig. 2.—Three exposures of the Orion Nebula with slit positions marked. (Scale 15" per mm)
from it range from a high of $3 \times 10^4$ electrons/cm$^3$ at a point near the Trapezium to a low of $3 \times 10^2$ electrons/cm$^3$ at some of the faintest points observed in this investigation.

REFERENCES