

THE SPLITTING OF THE $2s^2 2p^3 \ ^2P$ TERM IN O II

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ABSTRACT

We have measured the O II $2p^3 \ ^2P_{1/2-2} \ ^2P_{3/2}$ and $^2D_{3/2-2} \ ^2D_{5/2}$ splitting in high-dispersion ($\sim 3 \text{ km s}^{-1}$ resolution), long slit CCD spectra of the bright planetary nebula NGC 7027. Techniques used to deblend the $^2D_{5/2-2} \ ^2P_{3/2,1/2}$, $^2D_{3/2-2} \ ^2P_{3/2,1/2}$ pairs of lines are described and applied to the data. Though accurate absolute wavelengths could not be obtained, accurate separations of the 2P , 2D levels were determined to be $2.00 \pm 0.03 \text{ cm}^{-1}$ and $20.11 \pm 0.07 \text{ cm}^{-1}$, respectively. The differences between these results and those of previous lower dispersion studies are attributed to the substantial differences in the relative intensities of the $^2D_{5/2-2} \ ^2P_{3/2,1/2}$ pair of lines which cause the blended line center to shift to longer wavelengths, thereby decreasing the estimated 2D separation.

Improved energy level values and improved wavelengths for [O II] are listed. The appropriate [O II] $2p^3 \ ^2P$ line ratios can provide good estimates of the density in the plasma and reddening along the line of sight. The $^2P_{1/2-2} \ ^2P_{3/2}$ transition at 60 GHz falls within an atmospheric O_2 band at the same frequency and has a rather small transition probability, so it is unlikely to be observable.

Subject headings: atomic processes — nebulae: planetary

I. INTRODUCTION

Wavelengths of forbidden lines of common ions can best be determined by combining laboratory and nebular measurements to obtain accurate energy levels. The advantages of both types of measurement, as well as earlier work in this field, are excellently summarized by Bowen (1955, 1960). In these two papers he carried out a very complete program of accurate measurements in bright planetary nebulae and provided (in the second paper) the best list of wavelengths available to this date. However, one term separation that he was unable to measure was the O II $2p^3 \ ^2P_{1/2-2} \ ^2P_{3/2}$ splitting. It is determined by the splitting of the [O II] doublets $^2D_{5/2-2} \ ^2P_{3/2,1/2} \ \lambda 7319.92$ and $^2D_{3/2-2} \ ^2P_{3/2,1/2} \ \lambda 7330.19$ (Bowen's measured wavelengths). Because of the relatively low speed of photographic plates in this spectral region, Bowen could not use extremely high dispersion to split these blended lines. His derived energy levels (Bowen 1960) are listed in Table 1. Sivjee, Romick, and Rees (1979) measured the wavelengths $\lambda \lambda 7320.1, 7330.2$ each ± 0.2 , in auroral spectra (with considerably lower resolution) thus approximately confirming Bowen's value for the $^2D_{5/2-2} \ ^2D_{3/2}$ splitting.

The best laboratory data were compiled and analyzed by Moore (1949). They are also listed in Table 1, where it can be seen that the best laboratory value of the $^2P_{1/2-2} \ ^2P_{3/2}$ splitting is 1.5 cm^{-1} . In an effort to improve this value, and thus the predicted wavelength of the corresponding radio-frequency line, we have endeavored to measure directly the splitting of the $\lambda \lambda 7319.92, 7330.19$ doublets, using a CCD detector at the coude focus of the Lick 3 m Shane reflector. At the same time, we also improved the measured value of the $^2D_{5/2-2} \ ^2D_{3/2}$ splitting.

II. OBSERVATIONS

The spectral data were obtained with a grating of 900 lines mm^{-1} used in the second order together with the 80 inch (200 cm) focal length camera and the 6.5 inch (16.5 cm) collimating mirror. The resulting dispersion in the relevant wavelength region was 2.46 \AA mm^{-1} . The detector was a three-phase TI 500×500 CCD with $15 \mu\text{m}^2$ pixels with an rms readout noise of 10 electrons (Lauer *et al.* 1984), giving a dispersion of $0.0369 \text{ \AA pixel}^{-1}$, or about $1.5 \text{ km s}^{-1} \text{ pixel}^{-1}$ in velocity space. The total wavelength coverage in a single exposure was then about 18 \AA . A slit width of $146 \mu\text{m}$ provided an instrumental resolution—taken to be the average full width at half-maximum (FWHM) of the comparison lamp emission lines—of 2 pixels, or about 0.074 \AA .

Planetary nebulae often have relatively strong [O II] emission, making them useful for such wavelength determinations. They are three-dimensional emission-line regions, however, in which the gas has significant radial motions on velocity scales much larger than our resolution element. Precise deblending techniques are then required to measure line separations to accuracies aimed at in this project: $\pm 0.01 \text{ \AA}$. To this end, two

TABLE 1
ENERGY LEVELS OF O II $2p^3$ CONFIGURATION

DESIGNATION	LEVEL (cm^{-1})		
	Moore 1949	Bowen 1960	This Paper
$^4S_{3/2}$	0.0	0.0	0.0
$^4D_{5/2}$	26808.4	26810.7	26810.5
$^2D_{3/2}$	26829.4	26830.5	26830.6
$^2P_{3/2}$	40466.9	40468.3	{ 40468.1
$^2P_{1/2}$	40468.4		

¹ Lick Observatory Bulletin, No. 1002.

75 minute exposures were taken with a long slit positioned just outside the bright knot of the high surface brightness planetary nebula NGC 7027—one scan centered at about $\lambda 7320$ and the other at $\lambda 7330$. Comparison spectra from a thorium-argon lamp were taken immediately after each of the exposures to enable wavelength calibration of the data. The spatial information provided by the detector allowed us to select the spectral rows corresponding to the “edge” of the nebula (at least as far as [O II] emission is concerned) where the line separation was cleanest, and the emission effectively at a single velocity. (The comparison lamp spectra used to derive the dispersion curves were taken from the same rows on the chip as the data, thereby minimizing possible effects resulting from slit misalignment.)

Splitting of the [O II] lines was evident in both reduced spectra in that there were double emission maxima, but because of the velocity structure of the nebula, the individual components were significantly blended. (In fact the FWHM of the individual reduced components was 23 pixels, or 35 km s^{-1} in velocity space.) It also was apparent that the wavelength separation in the $\lambda 7320$ scan could not be measured to the desired accuracy of $\pm 0.01 \text{ \AA}$ since the “blue” component was several times weaker than the “red” and also was contaminated by a narrow atmospheric absorption feature (about 4 pixels at full width) centered about 3 pixels blueward of the apparent line center, making line position measurements more difficult. However, the strength and apparent symmetry of the “red” component on this scan made it an ideal template for deblending the components in the $\lambda 7330$ scan. In fact, the adopted template was manufactured by reflecting the red half of this “red” component about its center.

In the reduced $\lambda 7330$ scan the two components had very nearly the same intensity. An atmospheric feature similar to that in $\lambda 7320$ scan contaminated the “red” component in this scan but fortunately was far enough to the red of line center to permit a determination of the line separation to within the desired accuracy. An iterative procedure was used to determine the positions of the line centers in that the adopted template was shifted, scaled, and subtracted from the $\lambda 7330$ scan in an attempt to most thoroughly remove each of the emission components. The line centers could then be objectively determined by minimizing the mean and standard deviation of the residuals after the subtraction (i.e., equivalent to finding the minimum of a three-dimensional surface). With one component removed, the other component was treated in a similar fashion. The atmospheric feature was “masked out” during the quantitative analysis. It is estimated that this technique could determine the relative positions of the line centers to ± 0.2 pixel.

Mainly as a consistency check, the same analysis was carried

out on the $\lambda 7320$ scan, and the line separation was indeed found to be consistent with that of the $\lambda 7330$ scan, but with a larger uncertainty: ± 0.20 pixel for the position of the strong “red” component, but ± 0.60 pixel for the weak contaminated “blue” profile. The line positions (in both air and vacuum), separations, and error estimates are summarized in Table 2. The errors in the absolute line positions are large because no attempt was made to correct for other known systematic velocity effects (e.g., the radial velocity of NGC 7027 itself, etc.). This would have required obtaining several more spectra containing lines of accurately known wavelength in the same spectral region, at the same point in the nebula. The line separation is, however, known to much higher accuracy. The formal error in this separation associated with the dispersion term in the linear fit calculated from the comparison spectra is less than $\pm 0.0001 \text{ \AA}$.

Line positions could be determined by two independent methods using either the linear dispersion curves derived from the thorium-argon comparison lines, or through the proper identification of the sharp atmospheric absorption features noted above which were found near the wavelengths of interest in each scan. Both methods yielded identical wavelengths for the four lines to $\pm 0.01 \text{ \AA}$. We emphasize that the line positions given in Table 2 are not absolute, but the relative separations are known to the quoted accuracy. In particular the ${}^2D_{3/2}$ - ${}^2D_{5/2}$ separation is $10.79 \pm 0.035 \text{ \AA}$. The error given is an upper limit. Because there were three unblended lines in the comparison spectra common to both grating settings, a weighted (by intensity) mean error could be computed which was indicative of the error in relative position estimates between the two scans. Bowen (1955, 1960) lists this separation as $10.27 \pm 0.14 \text{ \AA}$, although a value of $10.62 \pm 0.16 \text{ \AA}$ follows from his more accurately measured 4S - 2D wavelengths $\lambda\lambda 3726.05, 3728.80$, each $\pm 0.02 \text{ \AA}$. Sivjee, Romick, and Rees (1979) give approximately the same separation from auroral measurements. Neither of these studies could resolve the splitting of the 2P components, so substantial intensity differences between the close components would adversely affect the estimates of the 2D separation. In fact our observations have shown that while the two components of $\lambda 7330$ have about the same intensity, the $\lambda 7320$ components have substantially different intensities. The separation between the mean of the $\lambda 7330$ pair and the stronger of the $\lambda 7320$ pairs is 10.26 \AA , almost exactly the separation measured by Bowen. This strongly suggests that the discrepancy between the 2D splittings is a result of the low resolution of the previous studies and of the large intensity ratio in the $\lambda 7320$ pair.

It is possible to estimate the expected relative intensity ratios of the line pairs in different density regimes using atomic data

TABLE 2
WAVELENGTHS AND SEPARATIONS

TRANSITION	WAVELENGTH (\AA) ^a		WAVENUMBER (cm^{-1}) Vacuum	SEPARATION	
	Air	Vacuum		\AA	cm^{-1}
${}^2D_{5/2}$ - ${}^2P_{1/2}$	7318.79	7320.80	13659.71	1.080(+0.025)	2.01(+0.05)
${}^2D_{5/2}$ - ${}^2P_{3/2}$	7319.87	7321.88	13657.69		
${}^2D_{3/2}$ - ${}^2P_{1/2}$	7329.58	7331.60	13639.59	1.073(± 0.015)	2.00(± 0.03)
${}^2D_{3/2}$ - ${}^2P_{3/2}$	7330.65	7332.67	13637.60		
${}^2D_{5/2}$ - ${}^2D_{3/2}$	10.79 (± 0.03)	20.11(± 0.07)

^a Uncorrected for systematic velocity effects. For this reason the wavenumbers here refer not to the absolute values listed in Table 1, but the reciprocal of these vacuum wavelengths to the same number of places.

TABLE 3
CALCULATED LINE INTENSITY RATIOS

N_e (cm^{-3}) ($T = 10^4$ K)	$I(7320+)$ $I(7320-)$	$I(7330+)$ $I(7330-)$	$I(7320)$ $I(7330)$
0	3.02	0.96	1.24
10^3	3.13	0.99	1.25
10^4	3.07	0.97	1.25
10^5	3.04	0.96	1.24
10^6	3.15	1.00	1.26
10^7	3.55	1.12	1.29
10^8	3.77	1.19	1.31
10^9	3.80	1.19	1.32
Observed	≥ 1	~ 1	1.2

for O⁺ from Pradhan (1976), Eissner and Zeppen (1981), and Zeppen (1982). The calculated ratios for $T = 10^4$ K are shown in Table 3, along with observed values estimated from our spectra for the doublet ratios and $I(7320)/I(7330)$ taken from Kaler *et al.* (1976). (The calculated results are not at all sensitive to the assumed temperature.) In the low density limit, (as N_e approaches 0) the excitation of the 2P level is entirely due to collisional excitation from the ground 4S level. The intermediate limit (where N_e is greater than the critical densities for the 2D levels— $\sim 10^3$ cm^{-3} , but less than the critical densities for the 2P levels— $\sim 5 \times 10^6$ cm^{-3} , so collisional excitations from the 2D levels are also significant) is not essentially different from the low-density limit. The high-density regime (where N_e is greater than the critical density of both 2P levels and the populations of these levels are therefore governed by the Boltzmann equation) has the “red” components of the lines enhanced by about 25% compared to the low-density regime. While it has been suggested that an electron density $N_e \approx 6 \times 10^4$ cm^{-3} describes NGC 7027 best (e.g., Atherton *et al.* 1979), there undoubtedly is a wide range of densities in this nebula, and it is entirely possible that the $\lambda\lambda 7320, 7330$ emission comes from a region with density near $\sim 10^6$ cm^{-3} . In fact the observed ratios are more or less consistent with this latter suggestion and thus confirm that the discrepancy between the earlier 2D level separation measurement and our measurement is a result of the different intensities of the $\lambda 7320$ lines.

The weighted mean separation from Table 2, corresponding to the $^2P_{3/2}-^2P_{1/2}$ splitting, is thus 2.00 ± 0.03 cm^{-1} , giving a predicted frequency for this transition 60.0 ± 0.8 GHz, or a predicted wavelength 0.500 ± 0.006 cm. The error in the laboratory value listed by Moore is evidently larger than ± 0.1 cm^{-1} but well below ± 1 cm^{-1} .

III. DISCUSSION

The combination of our measured results with those of Bowen leads to improve energy level values. For the 2D splitting we adopt 20.1 ± 0.1 cm^{-1} ; the weighted mean of our determination from the near-infrared lines, 20.11 ± 0.07 cm^{-1} , and Bowen's from the ultraviolet lines, 19.8 ± 0.2 cm^{-1} . For the $^4S-^2D$ separation we take the average of $^4S-^2D_{3/2}$ and $^4S-^2D_{1/2}$ as measured by Bowen. The 2P splitting 2.00 ± 0.03 cm^{-1} is our determination. As discussed above, we take Bowen's measurements of $\lambda\lambda 7319.92, 7330.19$ to represent the $^2D_{5/2}-^2P_{3/2}$ and $^2D_{3/2}-^2P_{1/2,3/2}$ (straight average) wavelengths. Taking the straight average of these two determinations of the 2P energy gives the values listed in the last column of Table 1. It is interesting to note that Godefroid and Fischer (1984) calculated a splitting of 2.6 cm^{-1} for the 2P term, in much better

TABLE 4
WAVELENGTHS OF [O II] LINES

Transition	λ (Å, air)
$^4S-^2D_{3/2}$	3726.03
$^4S-^2D_{5/2}$	3728.82
$^4S-^2P_{1/2}$	2470.21
$^4S-^2P_{3/2}$	2470.33
$^2D_{3/2}-^2P_{1/2}$	7329.63
$^2D_{5/2}-^2P_{1/2}$	7318.85
$^2D_{3/2}-^2P_{3/2}$	7330.70
$^2D_{5/2}-^2P_{3/2}$	7319.92

agreement with our new experimental determination than any previous theoretical calculation.

These energy levels in turn give the improved wavelengths (in air) listed in Table 4. Note in particular the best value for the $\lambda 3727$ splitting is 2.79 ± 0.01 Å, not 2.75 Å as determined from the earlier optical measurements alone.

Observation of [O II] transitions from the $2p^3\ ^2P$ term can provide information on the physical conditions in the emitting plasma and on the reddening along the line of sight. The critical densities (at which collisional transition out of the level occur at the same rate as radiative ones) are $4.3 \times 10^6 T_4^{1/2}$ cm^{-3} and $6.4 \times 10^6 T_4^{1/2}$ cm^{-3} for transitions from $^2P_{1/2}$ ($\lambda 7330-$, $\lambda 7320-$, $\lambda 2470-$) and $^2P_{3/2}$, respectively. As indicated in Table 3, measurements of the line ratios $I(7330+)/I(7330-)$ and $I(7320+)/I(7320-)$ could be used to infer densities in this regime, if the lines were sufficiently narrow to be resolved.

Line ratios such as $I(7320+)/I(2470+)$ can be used as a direct measure of the reddening; the intrinsic value is 0.70 based on the transition probabilities calculated by Zeppen (1982). Even if the line components cannot be resolved (the splitting of the $\lambda 2470$ line is only 0.12 Å), the ratio of the blended lines is almost independent of temperature and density and remains a good reddening indicator:

$$\frac{I(7320)}{I(2470)} = 0.70 \left[\frac{1 + I(7320-)/I(7320+)}{1 + 0.78 I(7320-)/I(7320+)} \right]$$

varies by less than 1% as N_e varies from 0 to ∞ according to the results in Table 3.

In principle, O⁺ could also be observed via the $^2P_{1/2}-^2P_{3/2}$ transition at 60 GHz, but this is impractical both because the line is centered on the atmospheric O₂ band at 60 GHz (Allen 1963) and because the transition probability

$$A_{ij} = 2.1 \times 10^{-11} \text{ s}^{-1}$$

(Zeppen 1982) is too small. (It is 12 orders of magnitude smaller than that of a hydrogen recombination line at the same wavelength.)

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