MEASUREMENTS OF THE SINGLY IONIZED OXYGEN AURORAL DOUBLET LINES $\lambda\lambda$7320, 7330 USING HIGH-RESOLUTION SKY SPECTRA

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ABSTRACT

The wavelengths of the individual [O ii] $2s^22p^3\,^2D_{5/2}^o\!-\!2s^22p^3\,^2P_{1/2,3/2}^o\,\lambda7320$ and [O ii] $2s^22p^3\,^2D_{5/2}^o\!-\!2s^22p^3\,^2P_{1/2,3/2}^o\,\lambda7330$ auroral doublet component lines have been measured directly in the nightglow for the first time, from high-resolution spectra obtained with the High Resolution Echelle Spectrophotometer (HIRES) spectrograph on the Keck I telescope at the W. M. Keck Observatory. Specifically, we find doublet splittings of $0.800 \pm 0.003$ Å and $0.808 \pm 0.003$ Å at $\lambda7320$ and $\lambda7330$, respectively, with the former significantly larger than the often quoted and utilized value of 0.8 Å from Moore and in line with the National Institute of Standards and Technology (NIST) (1.07 Å) as well as more recent astrophysical observations of the lines in planetary nebulae, including $1.07$ Å from De Robertis, Osterbrock, & McKee and 1.09 Å from Barnett & McKeith. Our results suggest, however, that adjustments of $+0.124$ Å and $+0.131$ Å should be made to current NIST wavelengths for the blue and red components of the $\lambda7320$ doublet respectively, while our wavelengths of the $\lambda7330$ doublet components are little changed from current NIST values. The observed intensity ratio of $\lambda7320/\lambda7330$ from these measurements agrees with the theoretical value calculated under conditions of thermally populated $^2P^o$ levels.

Subject headings: atomic data — methods: data analysis — techniques: spectroscopic

1. INTRODUCTION

The auroral [O ii] $2s^22p^3\,^2D_{5/2}^o\!-\!2s^22p^3\,^2P_{1/2,3/2}^o\,\lambda7320$ and [O ii] $2s^22p^3\,^2D_{5/2}^o\!-\!2s^22p^3\,^2P_{1/2,3/2}^o\,\lambda7330$ emission-line doublets are readily visible in the spectra of low-ionization astrophysical plasmas such as planetary nebulae (Bowen 1955, 1960; De Robertis, Osterbrock, & McKee 1985; Sharpee et al. 2003) and H II regions (Baldwin et al. 2000; Kennicutt, Bresolin, & Garnett 2003), where the levels of the $O^+\,^2P^o$ term are populated by collisions between thermal electrons and O$^+$ ions in the $4s^2$ ground term (Osterbrock 1989). As such, their strengths can be used to determine the electron density in the moderate density regime ($10^5$–$10^6$ cm$^{-3}$) of these objects (Barnett & McKeith 1988) and are commonly employed in combination with the nebular [O ii] $2s^22p^3\,^4S^o\!-\!2s^22p^3\,^2D_{1/2,3/2}^o\,\lambda\lambda$7263.0, 7298.15 lines to measure electron temperature (Seaton & Osterbrock 1957; Keenan et al. 1999). The doublets are also an important component of the auriglow and aurora, where $O^+\,^2P^o$ is produced primarily by photoionization of atomic O by solar extreme ultraviolet photons ($\lambda < 666$ Å) and electron-impact ionization (with energy <1 keV), respectively. Their altitude-dependent emission strength is used to calculate the quenching rate of $O^+\,^2P^o$ ions through collisions with N$\_2$ and atomic O (Rusch, Torr, & Hays 1977; Chang et al. 1993; Stephan et al. 2003), the altitude density profile of $O^+\,^2P^o$ and photoionization rate of atomic O (McDade et al. 1991), and the ion convection velocity and O$^+$ gas temperature in the ionospheric F layer (Smith et al. 1982; Cierpka et al. 2003). The intensities and line widths of the $\lambda\lambda$7320, 7330 doublet components have also been employed to detect the existence and characteristics of a permanent “hot” atomic oxygen corona existing above an altitude of 550 km (Yee, Meriwether, & Hays 1980).

We believe two recent studies demonstrate the necessity of determining and publicizing accurate energies for the O$^+\,2s^22p^3$ levels, particularly the wavelengths and splitting of the $\lambda\lambda$7320, 7330 doublet components. In their auroral data from their imaging Fabry-Perot interferometer, Cierpka et al. (2003) measured a $\lambda7320$ doublet separation of 0.796 Å from their fit to the separable unresolved, combined profile of their observed $\lambda7320$ component lines, close to the 0.8 Å (1.5 cm$^{-1}$) that they quote from Smith et al. (1982). However, their study could completely resolve the separate lines because of their large intensity difference. Moreover, recent ab initio and astrophysically observed calculations of the splitting argue for a significantly larger separation (see Table 1). Indeed, the newer values of the separation are larger than the 0.8 Å quoted from Smith et al. (1982) and measured by Cierpka et al. (2003) by the order of the typical 0.1–0.8 km s$^{-1}$ ion-drift velocities targeted for measurement by both studies. A larger $\lambda7320$ separation also calls into question both the Cierpka et al. (2003) interpretation of their observed line profile as the actual $\lambda7320$ pair and the accuracy of their F layer temperature determination, made from a line-profile fit in which the separation itself was a free parameter. Meanwhile, in their recent high-resolution spectra of the Orion Nebula, Baldwin et al. (2000) found that the differences between their observed $\lambda\lambda$7276, 7298 and tabulated National Institute of Standards and Technologies (NIST) wavelengths, after correction for nebular proper motion, is in good agreement with the same differences for the $\lambda7330$ components, but is systematically larger (by $\approx 5$ km s$^{-1}$ = 0.15 Å) than the same differences for the $\lambda7320$ components, even though all lines should originate in the same portion of the nebula. This discrepancy is a significant fraction of the total range of ionization-energy–dependent velocities seen in the Orion Nebula outflow (Baldwin et al. 2000).

High-resolution spectroscopy of the night sky has been shown to be a valuable tool for direct measurements of the line-rest wavelengths (Slanger et al. 2000). Presented here are
what we believe to be the first direct measurements in the airglow of the $\lambda\lambda 7320, 7330$ doublet-component wavelengths in which the doublets can be clearly resolved into their component lines. These measurements have been used to reevaluate the energy levels of the $^2D^o$ and $^2P^o$ terms, with the aim of improving their accuracy for use in the types of studies involving precision measurements of drift and nebular velocities, such as those mentioned above.

2. OBSERVATIONS AND REDUCTIONS

Sky spectra were drawn from among those to be archived in the observed National Virtual Astronomical Observatory (NVAO)$^3$ (Huestis, Cosby, & Slanger 2002) showing the most prominent $\lambda\lambda 7320, 7330$ lines, which were clearly distinguishable from and/or deemed clearly stronger than other neighboring telluric emission. These sky spectra were all obtained with the High Resolution Echelle Spectrophotometer (HIRES; Vogt et al. 1994) on the Keck I telescope at the W. M. Keck Observatory, and were originally associated with numerous deep-sky astronomical targets. The nominal instrumental resolution was in all cases 45,000 ($R \approx 6.7 \text{ km s}^{-1}$). Only spectra that had both doublets in the same order (echelle orders 48 or 49) were chosen, so as to minimize any wavelength and flux calibration errors, which are often associated with echelle spectra. An observation journal is given in Table 2.

All HIRES sky spectra were delivered to the NVAO archive, extracted, and reduced through wavelength calibration using the MAKEE$^2$ reduction routines developed by T. A. Barlow. Line wavelengths were determined by manually fitting a Gaussian and a straight line, representing the local continuum, to each line profile. Fluxes were determined by summing the counts under the fitted function. As can be seen in Figure 1, the high resolution of the HIRES spectra completely separates the doublet components and neighboring OH telluric lines, and profiles were well represented by Gaussian fits.

Besides the HIRES data, the tabulated $\lambda\lambda 7320, 7330$ line wavelengths (in air) from De Robertis et al. (1985; planetary nebula NGC 7027: $R = 100,000 = 3 \text{ km s}^{-1}$) and the $\lambda\lambda 7320, 7330$ lines remeasured from the spectra of Baldwin et al. (2000; Orion Nebula: $R = 30,000 = 10 \text{ km s}^{-1}$) and Sharpee et al. (2003; planetary nebula IC 418: $R = 33,000 = 9 \text{ km s}^{-1}$) were used to supplement the HIRES data. Bowen (1960), Baldwin et al. (2000), and Sharpee et al. (2003) were also used for the wavelengths of the $\lambda\lambda 3726, 3729$ lines that are too weak to be seen in the airglow.

3. CALCULATIONS

The tabulated wavelengths of the following OH Meinel band (8-3) lines from Goldman et al. (1998), $P_{11}(2.5)$ $\lambda\lambda 7316, 282, P_{22}(2.5)$ $\lambda\lambda 7329, 148, P_{11}(3.5)$ $\lambda\lambda 7340, 885$, and $P_{22}(3.5)$ $\lambda\lambda 7358, 667$, if present in the same HIRES echelle order as $\lambda\lambda 7320$ and $\lambda\lambda 7330$, were compared to measured wavelengths and used to normalize each HIRES spectrum to the same wavelength system. A weighted average of differences between the measured and tabulated wavelengths was

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1 See http://www.nvao.org.

2 See http://spider.ipac.caltech.edu/staff/tab/makee/.

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### Table 1

| Term       | Moore (1949) | Bowen (1960) | Fawcett (1975) | DOM (1985)$^a$ | Eriksson (1987) | MKM (1993)$^b$ | TFF (2002)$^c$ | This Work |
|------------|--------------|--------------|---------------|---------------|----------------|---------------|---------------|-----------|
| $^4S^1_2$   | 0.0          | 0.0          | 0.0           | 0.0           | 0.0            | 0.0           | 0.0           | 0.0       |
| $^2D^0_{3/2}$ | 26808.4      | 26810.7      | 26810.7       | 26810.5       | 26810.5        | 26810.5       | 26810.7       | 26810.7   |
| $^2D^0_{5/2}$ | 26829.4      | 26830.5      | 26830.6       | 26830.6       | 26830.7        | 26830.7       | 26830.5       | 26830.5   |
| $^2P^0_{3/2}$ | 40466.9      | 40466.3      | 40467.5       | 40466.1       | 40467.9        | 40468.0       | 40468.3       | 40467.9   |
| $^2P^0_{1/2}$ | 40468.4      | 40466.0      | 40470.1       | 40469.9       | 40470.0        | 40470.0       | 40469.9       | 40469.9   |

### Table 2

| Date (UT) | UT | Exposure (s) | Altitude | Azimuth | R.A. (J2000.0) | Decl. (J2000.0) | Slit (arcsec) | Observers$^a$ |
|-----------|----|--------------|----------|---------|---------------|----------------|---------------|---------------|
| 1993 Nov 15........ | 04:33 | 150 | 80.97 | 4.50 | 21 51 11.1 | +28 51 53.5 | 0.861 x 14.0 | 1 |
| 1993 Nov 15........ | 05:05 | 3000 | 53.94 | 182.41 | 22 15 27.2 | −16 11 33.0 | 0.861 x 14.0 | 1 |
| 1996 Aug 07........ | 05:49 | 300 | 35.70 | 277.81 | 12 41 51.9 | +17 31 22.3 | 0.861 x 14.0 | 2 |
| 1999 Jun 14........ | 05:39 | 600 | 58.42 | 324.19 | 11 05 30.9 | +43 31 13.5 | 0.861 x 7.0 | 3 |
| 1999 Jun 14........ | 05:54 | 1200 | 54.92 | 313.35 | 10 47 12.7 | +40 26 46.4 | 0.861 x 7.0 | 3 |
| 1999 Jun 14........ | 06:17 | 2400 | 50.97 | 310.57 | 10 47 13.9 | +40 26 53.1 | 0.861 x 7.0 | 3 |
| 1999 Jun 14........ | 14:13 | 2400 | 58.61 | 84.75 | 23 34 39.5 | +19 33 04.5 | 0.861 x 7.0 | 3 |
| 1999 Jun 15........ | 05:40 | 600 | 57.73 | 323.12 | 11 05 31.4 | +43 31 20.2 | 0.861 x 7.0 | 3 |
| 1999 Jun 15........ | 05:54 | 3000 | 54.25 | 312.81 | 10 47 14.1 | +40 26 53.7 | 0.861 x 7.0 | 3 |
| 1999 Jun 15........ | 14:21 | 1800 | 75.12 | 91.88 | 22 35 49.1 | −18 40 30.9 | 0.861 x 7.0 | 3 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ Observed by: (1) W. L. W. Sargent, J. K. McCarthy; (2) M. Rauch, L. Lu; (3) I. N. Reid, J. D. Kirkpatrick, A. J. Burgasser, J. Liebert.
calculated for each HIRES data set, with the above lines receiving weights of 4, 10, 2, and 1, respectively, roughly proportional to their relative theoretical intensities. These corrections, ranging in magnitude from 0.1–2.7 km s\(^{-1}\) (0.002–0.066 Å at 7325 Å), were applied to all measured wavelengths in each HIRES spectrum. The statistical scatter between tabulated and observed wavelengths after correction wavelengths in each HIRES spectrum. The statistical scatter between tabulated and observed wavelengths after correction was 0.5 km s\(^{-1}\) (≈0.01 Å at 7325 Å).

A linear \(\chi^2\) fit was then performed to simultaneously determine the best set of shared \(\lambda\lambda3726, 3729\) and \(\lambda\lambda7320, 7330\) observed air wavelengths for all data sets in which the lines were contained, from which a Doppler shift to correct for any residual internal kinematic and proper motion could be determined and applied to all nebular data (except data from Bowen 1960, which are averages from numerous planetary nebulae). The minimized merit function took the form

\[
\chi^2 = \sum_i \sum_j w_j \left| \lambda_{\text{obs},j}^i - (\lambda_{\text{best}}^i + \delta_j) \right|^2,
\]

where \(i\) and \(j\) are sums over all lines (\(\lambda\lambda3726, 3729\) and \(\lambda\lambda7320, 7330\)) and data sets, respectively; \(w_j\) are arbitrary weights given to each data set (see below); \(\lambda_{\text{obs},j}^i\) are the wavelengths of each line, if observed, in each data set; \(\lambda_{\text{best}}^i\) the best shared wavelength for each line; and \(\delta_j\) the Doppler shifts (in Å) applicable to each nebular data set. In total, six line wavelengths, one for each \(\lambda\lambda3726, 3729\) and \(\lambda\lambda7320, 7330\) line, and three Doppler shifts, one for each nebular data set except for Bowen (1960), were determined in this manner.

The weights \(w_j\) (0.018 for Bowen 1960; 0.16 for DeRobertis et al. 1985; 1.00 for Baldwin et al. 2000 and Sharpee et al. 2003; and 10.00 for all HIRES data) were arbitrarily chosen to best represent our perceived accuracy of the measurements involved, with nebular data sets generally receiving lower values because of unknown amounts of residual internal kinematic and proper motions.

Following conversion of all observed line wavelengths to vacuum wavenumbers (cm\(^{-1}\)), linear \(\chi^2\) fits were made to each level and term-splitting value as combinations of those wavenumbers:

\[
\chi^2 = \sum_j w_j \left[ \Delta(2D^e - 4S^e) - \frac{1}{2} (\nu_{3726,j} + \nu_{3729,j}) \right]^2,
\]

\[
\chi^2 = \sum_j w_j \left[ \Delta(2P^e - 2D^e) - \frac{1}{2} (\nu_{7319,j} + \nu_{7331,j}) \right]^2 + w_j \left[ \Delta(2P^o - 2D^e) - \frac{1}{2} (\nu_{7320,j} + \nu_{7331,j}) \right]^2,
\]

\[
\chi^2 = \sum_j w_j \left[ \Delta(2D^o) - (\nu_{3726,j} - \nu_{3729,j}) \right]^2 + w_j \left[ \Delta(2D^e) - (\nu_{3719,j} - \nu_{7330,j}) \right]^2 + w_j \left[ \Delta(2D^o) - (\nu_{7320,j} - \nu_{7331,j}) \right]^2,
\]

\[
\chi^2 = \sum_j w_j \left[ \Delta(2P^o) - (\nu_{7319,j} - \nu_{7320,j}) \right]^2 + w_j \left[ \Delta(2P^e) - (\nu_{7330,j} - \nu_{7331,j}) \right]^2,
\]

where \(\Delta\) applies to the wavenumber differences between each level and term-splitting value as combinations of those wavenumbers.
where \( w_j \) are the data-set weights (here equal to 1 except for the case noted below); \( \Delta(2^D - 4^S) \) and \( \Delta(2^P - 2^D) \) are the energy differences (in cm\(^{-1}\)) between the \( 2^D \) and \( 4^S \) and the \( 2^P \) and \( 2^D \) terms, respectively; \( \Delta(2^P) \) and \( \Delta(2^P) \) are the fine-structure energy level splitting; and \( \nu_j \) are the observed vacuum wavenumbers of all lines from the \( j \) data sets where available, corrected for any Doppler shift determined from the previous fit (nebular sources only). The Bowen (1960) data were not included in the \( \Delta(2^P) \) fitting, and its data were given a weight \( (w_j = 0.5) \) for purposes of the \( \Delta(2^P - 2^D) \) fit. The energy of each term was taken to lie exactly between the fine-structure level energies.

The resulting energy levels, line vacuum wavenumbers, and line air wavelengths are listed in Table 3. Listed errors are the 2 \( \sigma \) formal uncertainties from the correlation matrices of the various fits, propagated through the equations for line vacuum wavenumbers as combinations of energy levels and term splittings:

\[
\begin{align*}
\nu_{\lambda 7326} &= \Delta(2^D - 4^S) + \frac{1}{2} \Delta(2^D), \\
\nu_{\lambda 7329} &= \Delta(2^D - 4^S) - \frac{1}{2} \Delta(2^D), \\
\nu_{\lambda 7319} &= \Delta(2^P - 2^D) + \frac{1}{2} \Delta(2^P) + \frac{1}{2} \Delta(2^D), \\
\nu_{\lambda 7330} &= \Delta(2^P - 2^D) - \frac{1}{2} \Delta(2^P) + \frac{1}{2} \Delta(2^D), \\
\nu_{\lambda 7331} &= \Delta(2^P - 2^D) - \frac{1}{2} \Delta(2^P) - \frac{1}{2} \Delta(2^D),
\end{align*}
\]

where all symbols have the same meanings as above. The trans-auroral lines at \( \lambda 2470.2, 2470.3 \), while not observed, were also calculated from the four fitted energy-level and term separations.

4. DISCUSSION

The doublet wavelength separation values determined here compare very favorably with what we consider to be the most accurately determined astrophysical values from Barnett & McKeith (1988; 1.09 \( \pm \) 0.02 \( \AA \) for \( \Delta(2^P) \) and 10.70 \( \pm \) 0.03 \( \AA \) for \( \Delta(2^D) \); specific line wavelengths were not reported), while their formal uncertainties exceed ours. The \( 2^D \) and \( 2^P \) term-splitting values fall in the middle of the range of those determined from more recent experimentally inferred and astrophysically observed values (see Table 1), although ours should be inherently more accurate given our direct measurement of the \( \lambda 7320, 7330 \) line wavelengths, as opposed to Ritz-method determinations from more easily observable UV lines in laboratory experiments. The measurements made here were not complicated by blending with other telluric features or significant thermal broadening of the lines, and thus did not rely upon potentially error-prone deblending techniques (e.g., De Robertis et al. 1985). Our measurements of the \( 2^P \) energy splitting along with other recent observationally determined values (Table 1) are consistently and significantly smaller than those determined from the recent theoretical calculations of Zeippen (1987; 3.0 cm\(^{-1}\) for their “A” configuration, 2.7 cm\(^{-1}\) for their “B” configuration) and Tachiev & Froese Fischer (2002; 2.58 and 2.60 cm\(^{-1}\) relating to ab initio and energy-corrected values, respectively), although the \( 2^D \) energy splitting values show much better agreement. Finally, the application of the new individual \( \lambda 7320, 7330 \) line wavelengths to the results of Baldwin et al. (2000) significantly reduces the scatter in velocity residuals around their observed wavelengths for these lines, from 2.4–8.0 to 2.2–2.7 km s\(^{-1}\).

Adoption of the new \( \lambda 7320, 7330 \) wavelengths would lead to an upward adjustment in the often utilized NIST values for the 7320 lines (7318.92 and 7319.99 \( \AA \)) by 0.124 and 0.131 \( \AA \), respectively, and a one-digit increase in the number of significant digits for which the wavelengths are known.

It appears likely that the splitting value for the \( 2^P \) term of 0.796 \( \AA \) determined by Cierpka et al. (2003) using their imaging Fabry-Perot interferometer was not that of the \( \lambda 7320 \) components. Their instrument’s free spectral range of 0.017 \( \AA \) is almost exactly 1/10 that of the measured 1.077 \( \AA \) \( 2^P \) splitting value determined here, resulting in an unfortunate blending of the lines in their observations. It is more likely that the splitting measured was actually between the stronger \( \lambda 7320.121 \) component and a neighboring strong OH line from a different order. We speculate that the 0.8 \( \AA \) splitting value quoted from Smith et al. (1982) may date back to Moore (1949; see Table 1) because their resolution was also insufficient to separate \( \lambda 7320 \). As noted here, Moore (1949) has been superseded by more recent determinations. The large differences between the wavelength and term splitting values determined here and other older and/or widely utilized values,

| Transition | Level (cm\(^{-1}\)) | Wavelength (air) (Å) | NIST (Å) | \( \Delta^\prime \) (Å) |
|------------|--------------------|----------------------|---------|-------------------|
| \( 4^S_{1/2} \rightarrow 2^P_{1/2} \) | 40469.98 ± 0.08 | 2470.220 ± 0.005 | 2470.219 | +0.001 |
| \( 4^S_{3/2} \rightarrow 2^P_{3/2} \) | 40467.97 ± 0.08 | 2470.343 ± 0.005 | 2470.341 | +0.002 |
| \( 4^S_{1/2} \rightarrow 2^D_{1/2} \) | 26830.06 ± 0.08 | 3726.032 ± 0.011 | 3726.032 | ... |
| \( 4^S_{3/2} \rightarrow 2^D_{3/2} \) | 26810.76 ± 0.08 | 3728.785 ± 0.011 | 3728.815 | −0.030 |
| \( 4^P_1 \rightarrow 2^P_{1/2} \) | 13651.62 ± 0.007 | 7319.044 ± 0.004 | 7319.92 | +0.124 |
| \( 4^P_1 \rightarrow 2^P_{3/2} \) | 13657.213 ± 0.007 | 7320.121 ± 0.004 | 7319.99 | +0.131 |
| \( 4^P_3 \rightarrow 2^P_{1/2} \) | 13639.613 ± 0.007 | 7329.675 ± 0.004 | 7329.67 | +0.005 |
| \( 4^P_3 \rightarrow 2^P_{3/2} \) | 13637.403 ± 0.007 | 7330.755 ± 0.004 | 7330.73 | +0.025 |

\* Correction to NIST to align with present values.
\* Calculated over the noted range.
warrant reconsideration of conclusions reached employing those standards, such as regarding F layer physical conditions (Smith et al. 1982; Cierpka et al. 2003) and nebular-velocity structure (Baldwin et al. 2000).

Intensities from individual \( \lambda 7320, 7330 \) lines have been measured in the four HIRES spectra showing the strongest \( \lambda 7320, 7330 \) lines and least amount of atomic Fraunhofer absorption from scattered moon or zodiacal light. The average line intensities normalized to the total \( \lambda 7320, 7330 \) intensity and the standard deviations of the averages are listed in Table 4. The bulk of the \( \lambda 7320, 7330 \) emission arises from altitudes between 150 and 300 km, and throughout most of this range quenching collisions with atomic O and N\(_2\) are faster than spontaneous emission (Stephan et al. 2003). Thus, it is a good approximation to assume that O\(^+\) level populations are thermalized and relative intensity measurements of \( \lambda 7320, 7330 \) lines are related only to spontaneous transition coefficients and statistical weights. This provides a check on the accuracy of O\(^+\) \( \lambda 7320, 7330 \) Einstein A-coefficient values, which are employed in a variety of astrophysical diagnostics, for, e.g., electron density (De Robertis et al. 1985; Barnett & McKeith 1988) and temperature (Keenan et al. 1999), reddening (De Robertis et al. 1985), and O\(^+\) nebular abundances (Liu et al. 2000).

Unfortunately in most of the HIRES spectra, the \( \lambda 7320, 7330 \) lines were positioned close to the blue edge of the echelle orders in which they appeared, as a consequence of the original observers’ chosen grating tilts. Coupled with these lines’ intrinsic weakness and confusion of the continuum level near Fraunhofer absorption features, even in those spectra with the smallest degree of contamination, the HIRES spectra are not optimal for intensity measurements of these lines, as reflected in the large measurement uncertainties. Still, the theoretical high-density-limit intensity ratios constructed from major astrophysical sources of transition coefficients (those listed in Table 4), are all encompassed within those standard deviations, and, with the possible exception of the \( \lambda 7319.044 \) line, do compare well with the observed values. Sivjee, Romick, & Rees (1979) has previously reported a \( \lambda 7320/\lambda 7330 \) auroral intensity ratio measurement of 1.55 ± 0.05, which exceeded their own calculation of the ratio’s theoretical limiting value, at high density, of 1.31 using Seaton & Osterbrock (1957) transition coefficients under maximum quenching conditions (altitude <200 km). A recalculation of the theoretical high-density-limit ratio using equations (1)–(6) of Sivjee et al. (1979) with more recent coefficients (from Table 4) yields values between 1.28 and 1.30, virtually unchanged from the earlier estimation. However, our measured \( \lambda 7320/7330 \) ratio of 1.3 is consistent with this value and with the high-density limit theoretical values constructed from Table 4.

De Robertis et al. (1985) and Barnett & McKeith (1988) have proposed the use of the \( \lambda 7320.121/\lambda 7319.044 \) intensity ratio as an electron-density diagnostic in the \( \approx 10^5–10^6 \) cm\(^{-3}\) density regime. The diagnostic takes advantage of the increase in the theoretical intensity ratio, from a value of \( \sim 3.0 \), below \( 10^5 \) cm\(^{-3}\), to a high-density value of 3.8 (as calculated from Table 4) at and above \( 10^5 \) cm\(^{-3}\), as electron collisional excitation from the \( ^2P^o \) term, and deexcitation increasingly contribute to the \( ^2P^o \) levels’ populations. The average value of the \( \lambda 7320.121/\lambda 7319.044 \) intensity ratio measured from the HIRES spectra is 3.1 ± 0.9, while values of 3.3 and 3.5 are measured from the blended profile of the \( \lambda 7320 \) doublet in two lower resolution Keck II Echelle Spectrograph and Imager (ESI) spectra in our possession, all of which are lower than the composite high-density–ratio value of 3.8. A lower value of the high-density limit-intensity ratio, as is suggested from the HIRES and ESI spectra measurements, would reduce the utility of the diagnostic.

A stronger than predicted \( \lambda 7319.044 \) intensity relative to the total multiplet intensity, as is suggested by the HIRES data, could be behind the observed smaller than predicted value of the \( \lambda 7320.121/\lambda 7319.044 \) intensity ratio. However, the large uncertainty in the line’s intensity measurement in the HIRES spectra, echoed by the large uncertainty in the measured intensity ratio, suggests that the difference between the observed and theoretical high-density values of the ratio is probably not statistically significant. The ESI spectra ratio values are closer to the composite theoretical high-density–ratio value of 3.8, and systemic errors introduced in the deblending of a \( \lambda 7320 \) profile composed of unequal intensity components could account for much of the difference. Significant contamination of the \( \lambda 7320, 7330 \) line intensities from the N\(_2\) first positive (5–3) band is ruled out, since the band head (at 7387.2 Å) and the strongest features, as predicted from a DIATOM (Huestis 1994)\(^3\) simulation of the band’s intensity at a typical mesospheric temperature of 200 K, are absent from any of the utilized spectra.

Curiously, the \( \lambda 7320.121/\lambda 7319.044 \) intensity ratios of 2.7 and 2.9 measured from the IC 418 and Orion Nebula spectra,

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**Table 4**

| Source | \( \lambda 7319.044 \) | \( \lambda 7320.121 \) | \( \lambda 7329.675 \) | \( \lambda 7330.755 \) |
|--------|----------------|----------------|----------------|----------------|
| Godefroid & Froese Fischer (1984)\(^b\) | 0.12 | 0.45 | 0.20 | 0.24 |
| Zeippen (1987)\(^c\) | 0.12 | 0.45 | 0.20 | 0.24 |
| Wiese, Fuhr, & Deters (1996)\(^d\) | 0.12 | 0.45 | 0.20 | 0.24 |
| Baldwin et al. (2000) | 0.14 | 0.41 | 0.22 | 0.23 |
| Sharpee et al. (2003) | 0.15 | 0.40 | 0.23 | 0.22 |
| This paper | 0.14 ± 0.05 | 0.43 ± 0.03 | 0.20 ± 0.04 | 0.23 ± 0.03 |

\(^a\) Normalized to sum of all multiplet lines, assuming statistically populated levels.

\(^b\) Values same within precision for both configuration calculations.

\(^c\) Configuration sets “A” and “B” with a theoretical energy correction and relativistic M1 values.

\(^d\) The source of NIST O\(^+\) values, consisting of the arithmetic average of Zeippen (1987) and Godefroid & Froese Fischer (1984), the latter modified with newer experimental wavelength data.

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\(^3\) See http://www-mpl.sri.com/software/diatom.html.
respectively, as calculated from Table 4, are slightly below the low-density value of 3.0, even though both objects have electron densities of \( \approx 10^4 \) cm\(^{-3} \). This may indicate that additional processes other than electron collisional excitation may be populating the \(^2P^0\) levels at rates not according to their statistical weights. For example, electron recombination of \(^O^2\) with a subsequent cascade (Liu et al. 2000) or photoionization of neutral O (Ferland & Truran 1981) are two processes that may also affect the nebular \( \lambda \lambda 7320, 7330 \) line intensities.

In summary, the HIRES data generally supports the accuracy of widely used astrophysical spontaneous transition coefficients, with some lingering problems that the present data sets’ large scatter and small numbers are unable to resolve.

5. CONCLUSIONS

We have used high-resolution HIRES sky spectra to accurately determine the wavelengths and relative intensities of the \( \lambda \lambda 7320, 7330 \) doublet lines, measured directly for the first time from completely resolved profiles in the airglow. These measurements are extremely accurate, given the nature and advantages of using sky spectra, as opposed to deducing the wavelengths from energy levels established by more easily observable transitions or from nebular line wavelengths corrected for proper and internal kinematics. The new wavelengths determined here differ by as much as 0.131 Å from the widely used NIST values, and the aeronomically important \( \lambda 7320 \) doublet-splitting value measured here differs by 0.277 Å from the “accepted” value of 0.8 Å still employed as recently as Cierpka et al. (2003). The magnitudes of these differences suggest that the interpretation of observations made by comparing against earlier standards may need to be revised. The observed fluxes for individual lines agree, within their sample scatter, with theoretical values calculated under the high-density limit that should prevail in the region of the atmosphere in which they are formed.

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