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Studying Atomic Physics Using the Nighttime Atmosphere as a Laboratory

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ABSTRACT

A summary of our recent work using terrestrial nightglow spectra, obtained from astronomical instrumentation, to directly measure, or evaluate theoretical values for fundamental parameters of astrophysically important atomic lines.

1. Introduction

While the terrestrial nightglow is dominated both in total emission intensity and numbers of emission lines by molecular emitters such as OH and O_2, emission lines corresponding to atomic transitions are also prevalent. The optically forbidden [O I] $2p^4\ {}^1D_2$-${}^1S_0$ λ5577 "green line" and [O I] $2p^3\ {}^3P_{2,1}$-${}^1D_2$ $\lambda\lambda$6300,6364 "red" lines are strong and well-known components of the nightglow. The high sensitivity of astronomical instrumentation also reveals much weaker features such as [N I] $2p^4\ {}^4S^o_{3/2}$-${}^2D^o_{3/2,5/2}$ $\lambda\lambda$5198,5200, the [O II] $2p^3\ {}^2D^o_{3/2,5/2}$–${}^2P^o_{1/2,3/2}$ $\lambda\lambda$7320,7330 doublets, and permitted transitions of neutral O arising from electron radiative recombination of O^+.

Many of these lines are present in low-ionization astrophysical plasmas such as those found in planetary nebulae and H II regions, and are used as diagnostics of their kinetics, physical conditions, and abundances. The use of these lines as diagnostics assumes accurate knowledge of their fundamental atomic parameters, namely wavelengths, spontaneous emission coefficients, and electron recombination cross-sections. Given that many of the emitting levels are metastable and therefore difficult to observe in the laboratory, a great reliance has been placed on theoretical calculations of these parameters. However, due to the rarefied nature of the atmosphere and the abundance of emitters in the nightglow layers, the nighttime sky acts as a laboratory where these parameters can either be directly measured or inferred, and compared to theoretical values.

Table 1: HIRES Measurements of Atomic Nightglow Line Wavelengths versus NIST

Atomic Line	HIRES λ (Å)	NIST λ (Å)	HIRES-NIST λ (Å)
Slanger et al., *J. Chem. Phys.*, 2000			
[O I] $2p^4\ {}^1D_2$–$2p^4\ {}^1S_0$	5577.335	5577.339	-0.004
[O I] $2p^4\ {}^3P_2$–$2p^4\ {}^1D_2$	6300.302	6300.304	-0.002
[O I] $2p^4\ {}^3P_1$–$2p^4\ {}^1D_2$	6363.780	6363.776	0.004
[N I] $2p^3\ {}^4S^o_{3/2}$–$2p^3\ {}^2D^o_{3/2}$	5197.922	5197.902	**0.020**
[N I] $2p^3\ {}^4S^o_{3/2}$–$2p^3\ {}^2D^o_{5/2}$	5200.281	5200.257	**0.024**
Sharpee et al., *Astrophys J.*, 2004			
[O II] $2p^3\ {}^2D^o_{5/2}$–$2p^3\ {}^2P^o_{1/2}$	7319.044±0.004	7318.92	**0.124**
[O II] $2p^3\ {}^2D^o_{3/2}$–$2p^3\ {}^2P^o_{1/2}$	7320.121	7319.99	**0.131**
[O II] $2p^3\ {}^2D^o_{5/2}$–$2p^3\ {}^2P^o_{3/2}$	7329.675	7329.67	0.005
[O II] $2p^3\ {}^2D^o_{3/2}$–$2p^3\ {}^2P^o_{3/2}$	7330.755	7330.73	**0.020**

2. Forbidden Line Wavelengths

The High Resolution Echelle Spectrometer (HIRES) on the Keck I telescope, W.M. Keck Observatory, has provided a wealth of individual nightglow spectra, which have been co-added together (∼100 hours) to provide a very high signal-to-noise spectrum that has been proven useful for transition wavelength measurements (Slanger et al. 2000). Wavelength calibration by ThAr lamp and comparison with numerous OH Meinel band system nightglow line wavelengths provide a level of accuracy of about 0.004Å. Comparisons with National Institute of Standards and Technology (NIST) wavelengths for various atomic lines, listed in Table 1, show good agreement for some lines, but poorer agreement for others.

Other HIRES nightglow spectra, supplemented by selected planetary nebula and H II region spectra, have been used to establish new energy levels for the $2p^3$ ground electron configuration of O II, and for inferring new wavelengths for the [O II] $\lambda\lambda$7320,7330 doublet lines (Sharpee et al. 2004). As can be seen in Table 1, the difference between NIST and observed values is quite substantial (upwards of 5.4 km s^{-1}) adversely affecting, for example, the use of these lines as a Orion Nebula outflow velocity indicator (Baldwin et al. 2000).

3. Diagnostic Line Intensity Ratios

Nightglow spectra from HIRES and the Echellette Spectrograph and Imager (ESI) on Keck II, have been used to measure the optically forbidden line intensity ratios [O I] $\lambda6300/\lambda6364$ and [N I] $\lambda5198/5200$. While not providing a direct determination of these lines' spontaneous emission coefficients, these measurements allow discrimination between competing and sometimes widely varying theoretical values.

For [N I] $\lambda5198/\lambda5200$, the observed value, 1.759±0.014, departs significantly from that

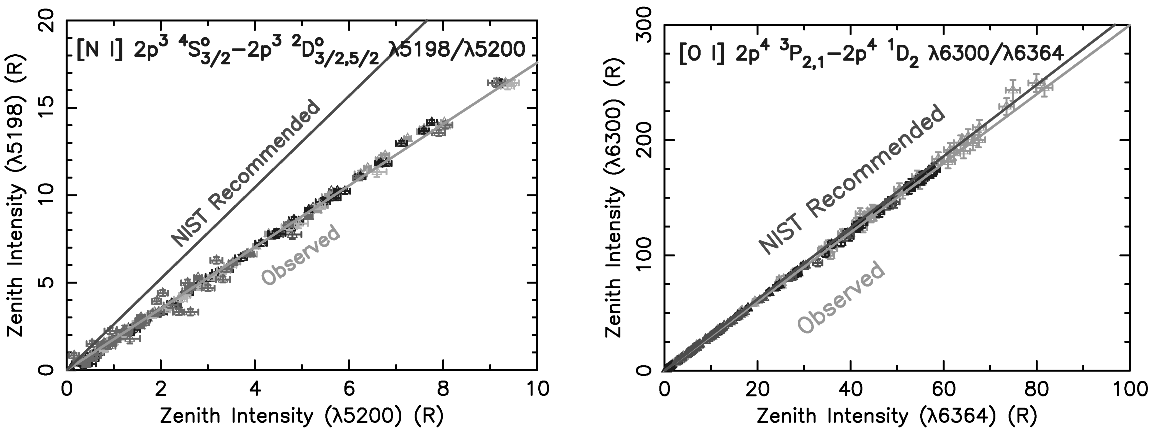

Fig. 1.— LEFT: [N I] $\lambda5198/\lambda5200$ intensity ratio from 190 HIRES and ESI nightglow spectra, best fit (1.759), and ratio determined from NIST spontaneous emission coefficients (2.61). RIGHT: Observed [O I] $\lambda6300/\lambda6364$, best fit (2.997), and NIST (3.10).

calculated with the spontaneous emission coefficients recommended by NIST (2.61), as is seen in Figure 1 (Sharpee et al. 2005). The ratio is used as an electronic density diagnostic, and the difference in densities determined using the NIST coefficients and those yielding the best agreement with observation can reach an order of magnitude for an observed ratio at typical nebular temperatures. By contrast, the observed [O I] $\lambda6300/\lambda6364$ ratio of 2.997 ± 0.016 shows better agreement with the consensus theory value of ~3.1 including NIST, as is seen in Figure 1 (Sharpee & Slanger 2006), but is slight lower reflecting the subtle effects of the inclusion of relativistic corrections to the magnetic dipole operator made during the recent coefficient calculation of Storey & Zeippen (2000).

4. Weak Permitted Lines From Electron Radiative Recombination of O^+

HIRES and ESI spectra have revealed numerous weak permitted lines of neutral oxygen that are produced by electron radiative recombination of O^+ to excited levels, and subsequent radiative cascade (Slanger et al. 2004). Recombination lines, while generally much weaker than their forbidden counterparts in planetary nebulae and H II regions, are the lines of choice for abundance determinations due to their insensitivity to variations in electron temperature and density along a line of sight through a nebula.

The effective recombination coefficients that directly link the intensities of these lines with parental abundances combine several fundamental parameters, including electron recapture cross-sections and cascade branching ratios. Line intensities from both the triplet and quintet sequences measured in HIRES and ESI spectra are found to be proportional to their effective recombination coefficients (Escalante & Victor 1992) by the same constant, the product of electron and O^+ densities, which in turn yields a sensible O^+ abundance for conditions likely to prevail in the ionosphere at the time of the observation. This validates their coefficient calculation methods, providing greater confidence in similar calculations made for other astrophysically important ions.

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