

IN-90
07/12/37

Laboratory Astrophysics under
the Ultraviolet, Visible, and Gravitational Astrophysics Research Program

Final Technical Report for Grant NAG5-6729
Oscillator Strengths for Ultraviolet Atomic and Molecular Transitions

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I. Introduction

Space-borne facilities, such as the *Hubble Space Telescope*, the recent ORFEUS-SPAS II Shuttle mission, and the soon-to-be launched *Far Ultraviolet Spectroscopic Explorer*, are providing data at ultraviolet wavelengths of unprecedented quality for spectroscopic studies of many astronomical environments. The first step in the analysis of these data involves the derivation of abundances. Obtaining accurate abundances is possible only when the correspondence between line strength and abundance is well known. The conversion of line strength to abundance relies on knowledge of transition probabilities and oscillator strengths, often obtained from mean lives branching fractions. For many ultraviolet transitions, the necessary atomic and molecular data are either relatively imprecise or not available. Our program addresses this need for accurate oscillator strengths: our focus is on transitions that probe the nature and composition of the interstellar medium.

II. Laboratory Results

Two experimental methods are employed by our research group to extract oscillator strengths. Beam-foil spectroscopic techniques are used to measure mean lives and branching fractions for atomic transitions at ultraviolet wavelengths. An ion beam of the desired element is accelerated and it passes through a thin carbon foil, where neutralization, ionization, and excitation take place. Mean lives are determined by measuring the decay of the excited state as a function of distance from the foil. Oscillator strengths are obtained from the mean life and branching fraction. The second technique involves absorption spectroscopy, where a gas cell containing the species of interest is placed in front of a source of ultraviolet radiation, such as a synchrotron. The measured absorption profiles are fitted to a theoretical profile to yield the amount of absorption from which the oscillator strength can be derived.

(i) Si II

For many lines of sight, the line at 1526 Å displays highly saturated profiles which are not well suited to the determination of the interstellar silicon abundance. For such observations, the much weaker line at 1808 Å, measured carefully by Bergeson and Lawler (1993), is the preferred choice for investigation of the amount of silicon present in the gas. However, along other lines of sight such as those toward quasars, where silicon is less abundant, the line at 1808 Å is too weak for reliable measurement. In this case, the line at 1526 Å, arising from transitions to the $3s^2 4s^2 S_{1/2}$ level, is not saturated, making it a good candidate upon which to base an analysis. As noted in the report for NAGW-3840, we concluded from our measurements that the f -value for this multiplet is now firmly established and may be used with confidence in future observations. The interstellar line at 1023 Å, arising from transitions to the $3s^2 5s^2 S_{1/2}$ level, may also be employed in interstellar studies. Here our experimental mean life indicates that a more precise test of theory awaits the conclusion of more extensive calculations. During the current reporting period our laboratory results have appeared in the *The Astrophysical Journal* (Schectman et al. 1998).

(ii) Ni II

Measurements of Ni II absorption from low density, warm material and higher density, cold diffuse gas (Sembach and Savage 1996) show that the largest range in depletion onto interstellar dust for these environments occurs for nickel. Thus, Ni II absorption in damped Ly- α systems is used to place constraints on the evolution of dust within the intervening galaxy over Hubble time scales (e.g., Prochaska and Wolfe 1996; 1997). Current analyses of Ni II abundance in interstellar environments rely on the oscillator strengths compiled by Morton (1991). These f -values come from the unpublished theoretical work of Kurucz (1989). Many of the lines listed by Morton (1991) appear in *HST* spectra of ρ Oph A, χ Oph, and ζ Oph, and Zsargó and Federman (1998) analyzed these high-quality measurements so that an accurate set of relative f -values is available for future studies. Since there are as yet no laboratory results that can be used to place these relative measures on an absolute scale, unlike the situations for S I (Federman and Cardelli 1995) and C I (Zsargó et al. 1997), the actual abundance for Ni II cannot yet be derived from observation.

We started a series of experiments to rectify this problem in a collaboration with Lawler and Fedchak at the University of Wisconsin – Madison. Our effort is focused on measuring branching fractions: 1) at Denison – for transitions above 2000 Å as a check on the results obtained at Wisconsin, and 2) at Toledo – for the important interstellar lines $\lambda\lambda$ 1709, 1741, 1751. The 1 m spectrometer associated with Toledo's beam-foil facility will disperse light from of Ni/Ar hollow cathode tube. Data will be collected on the lines near 1700 Å as well as for several lines above 2000 Å where precise radiometric calibration is possible. An argon mini-arc will be used to characterize the instrumental response between 1700 and 2000 Å. Our goal is to complete these experiments by 1999 May and to submit the results to *The Astrophysical Journal*.

(iii) CO

Carbon monoxide is the second most abundant molecule in interstellar space. Ultraviolet data obtained with the Goddard High Resolution Spectrograph on the *Hubble Space Telescope* yield high-quality spectra of the $A^1\Pi - X^1\Sigma^+$ ($v',0$) system of bands (e.g., Lambert et al. 1994). In order to extract the most reliable abundances, one is interested in the data for the weakest, optically thin bands, those with $v' \geq 7$. Unfortunately, the earlier theoretical and experimental data on oscillator strengths for these bands span a range of 20 - 30%, which is larger than the uncertainties associated with the astronomical measurements. A previously reported experiment conducted at the Synchrotron Radiation Center (SRC) of the University of Wisconsin-Madison (Federman et al. 1997) helped to resolve the cause for the differences among earlier experimental results.

We initiated another study at the SRC on the $B^1\Sigma^+ - X^1\Sigma^+$, $C^1\Sigma^- - X^1\Sigma^+$, and $E^1\Pi - X^1\Sigma^+$ bands. These CO bands, where factors of 2 differences appear among available results, will be seen in spectra acquired with the *Far Ultraviolet Spectroscopic Explorer*. David Knauth, a graduate student at the University of Toledo, was a key participant in this first effort. Future improved experiments are planned for the Summer of 1999 so that reliable data can be extracted for these far ultraviolet bands.

III. Astronomical Results

(i) S I

Many interstellar S I lines appear in the ultraviolet spectra of O and B stars. Comparison between these lines and the VUV lines of C I provides important information about the physical state of the gas (see Smith et al. 1991; Federman et al. 1993). For instance, Federman et al. derived the Doppler width from a suite of S I lines measured toward ζ Ophiuchi with *HST* and found that the width for atomic lines could not be represented by the two narrow components seen in molecular lines (e.g., Lambert et al. 1990). Federman et al. therefore surmised that the molecular material was in clumps within more widely distributed atomic gas. Detailed analysis of the spectra was hindered by limitations of the available observations and conflicting results on oscillator strengths, as noted in earlier reports to NASA. Our precise measurements conducted under earlier funding (Beideck et al. 1994) enabled Federman and Cardelli (1995) to extract from interstellar spectra toward ζ Ophiuchi taken with *HST* a set of self-consistent f -values for 27 lines of S I belonging to 14 multiplets. Comparison of their f -values with recent astronomical, experimental, and theoretical studies is excellent.

Lifetimes inferred from the f -values of Federman and Cardelli (1995) are in good agreement with the measured lifetimes of Berzins et al. (1997) and the results from the Opacity Project (Butler et al. 1999), especially for ns^3S^o and $4s''^3P^o$. However, the correspondence between the empirical results and theory is less satisfactory for the transitions involving a $3D^o$ upper state. We (Biémont et al. 1998a) therefore performed additional experiments (with Svanberg and Li in Lund, Sweden and with Garnir of Liège, Belgium) – including laser-induced fluorescence measurements – and carried out extensive computations (Biémont in Liège, Belgium) to extend the lifetime comparison between astronomically derived f -values and other determinations. Particular attention was given to decays from $8s^3S^o$ and $6d^3D^o$, and again, the agreement is quite good. Mixing among various $3D^o$ states, including that due to configuration interaction and spin-orbit interactions, appears to be the cause for the differences with the large-scale computations (see Martin et al. 1990; Beideck et al. 1994; Tayal 1997). This long-term effort of ours, involving beam-foil spectroscopy, analysis of *HST* data, laser experiments, and large-scale computations, have provided the astronomical community with a extensive set of f -values that they can use with confidence.

(ii) Co II

Federman et al. (1993) presented *HST* spectra which showed the first clear detection of interstellar Co II (λ 1466). This line, as well as the lines at 1448 and 1481 Å, were detected in interstellar gas toward ρ Oph A with *HST*. Through a collaborative effort with Lawler and Mullman at the University of Wisconsin – Madison, who determined absolute oscillator strengths for transitions in Co II that included $\lambda\lambda$ 1466, 1481, we were able to place the relative f -value for λ 1448 inferred astronomically on an absolute scale (Mullman et al. 1998). We were confident in doing this because the astronomical and experimental ratios, $f(1481)/f(1466)$, agreed very well. Our f -values are about a factor of 2 to 3 smaller than those of Kurucz (1989) recommended by Morton (1991), but are in close agreement with the large-scale calculations of Raassen et al. (1998). These measurements allowed us to determine the gas phase abundance (and depletion) of interstellar cobalt for the first time. Analysis of the *HST* data indicates cobalt no longer follows the trend expected for a refractory element in a plot of depletion versus condensation temperature. The physics underlying grain composition, therefore, is less well-understood than once believed.

IV. Conferences

The poster by Zsargó, which described the work on C I and Ni II at the conference *The Scientific Impact of the Goddard High Resolution Spectrograph*, has appeared in print (Zsargó et al. 1998a), as has the poster presented at ICAMDATA (Zsargó et al. 1998b); both were discussed in an earlier report. The latest work on S I was described by Biémont et al. (1998b, c) at two European conferences – *The Sixth European Conference on Atomic and Molecular Physics* and the *XVI International Conference on Atomic Physics*. Federman described our recent results in a poster at the *6th International Colloquium on Atomic Spectra and Oscillator Strengths* (Federman et al. 1999) which took place in Victoria, BC Canada in August of 1998. Finally, in an invited talk, Federman gave an overview of our recent results at a NASA Workshop on laboratory astrophysics held at Harvard's Center for Astrophysics in April of 1998.

V. References

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