Laboratory Data Needed in Support of the FUSE (Far Ultraviolet Spectroscopic Explorer) Mission

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The *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) will be launched within a few months. *FUSE* will obtain spectroscopic data in the wavelength interval from 916 to 1196Å with a nominal resolving power of $\lambda/\Delta\lambda = 30{,}000$ on a wide variety of astronomical sources with far-UV flux levels in the range from 10^{-14} to 10^{-10} erg $cm^{-2}sec^{-1}Å^{-1}$. This wavelength region has not been well-studied spectroscopically, and as a result fundamental data are lacking for a number of transitions of atoms, ions, and molecules. We expect to gather stellar and interstellar data for a wide variety of astrophysical problems including measurements of the D/H ratio, studies of hot gas in the interstellar and intergalactic media, observations of AGNs and quasars, observations of molecular hydrogen and other molecular species, studies of stellar winds and extended atmospheres, analyses of nebulae and supernova remnants, and general ISM abundances and depletions. We provide a list of species known to be of interest, in the hope that we can stimulate laboratory measurements of transition probabilities. We also invite input, suggestions, and data on species and transitions not in our list which may be relevent to the *FUSE* mission.

The *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), with launch expected in early 1999, will provide spectroscopic measurements of many atoms, ions, and molecules in the far ultraviolet. This spectral region has been probed at moderate or high spectral resolution previously by a only handful of instruments, such as *Copernicus* (Rogerson *et al.* 1973) and the ORFEUS-SPAS missions, which have deployed the *Interstellar Medium Absorption Profile Spectrograph* (*IMAPS*; Jenkins *et al.* 1996) and a Berkeley far-UV spectrograph (Hurwitz *et al.* 1998). *FUSE* will provide a wealth of data, for many different scientific purposes, in this spectral region, and new laboratory measurements will be needed to supplement the oscillator strength compilation of Morton (1991).

The best source of information on the *FUSE* mission is the *FUSE* homepage on the World Wide Web (http://fuse.pha.jhu.edu). To summarize, *FUSE* will provide spectral coverage from 916 to 1196Å at a nominal resolution of $\lambda/\Delta\lambda = 30{,}000$. The effective area varies with wavelength, as each spectrum will consist of four overlapping segments coming through different optical paths and utilizing different coatings designed to be optimal at different wavelengths. Current values for the effective area range from 20 to 70 cm^2, with a maximum in the important spectral region 1025 to 1070Å, where lines of O VI, Ar I, H I (Lyman-β) and H_2 are dominant.

The limiting flux for obtaining high S/N in reasonable times at this resolution is about 10^{-13} erg cm^{-2}sec^{-1}Å^{-1}. For lower flux levels, good S/N can be achieved by binning the data, resulting in a reduction in spectral resolving power (typically to $\lambda/\Delta\lambda = 5{,}000$). The sensitivity of *FUSE* is far superior to that of previous far-UV high-resolution instruments, providing access to an entirely new physical regime for detailed far-ultraviolet spectroscopic studies.

The science goals of the *FUSE* mission (based on the observing plans of the PI science team) include:

Measurement of the D/H ratio: *FUSE* will measure directly the ratio of atomic deuterium to atomic hydrogen in a wide range of environments. *FUSE* will be able to measure the D/H ratio in regions ranging from the local interstellar medium to intergalactic clouds. The overall goal of this program will be to test cosmological models by inferring the primordial D/H ratio.

Highly ionized gas in the interstellar medium: *FUSE* will make great strides in sampling highly ionized gas, both in our galaxy and in the halos of other galaxies, including the Magellanic Clouds and other Local Group systems. The principal highly ionized species accessible only to *FUSE* are O VI and S VI, but data on others such as N II, N III, C III, and S IV will also be uniquely accessible to *FUSE*.

Molecular hydrogen: The primary electronic transitions of H_2 lie within the *FUSE* wavelength band, thus making *FUSE* the only planned mission capable of observing the most abundant interstellar species. Two overlapping H_2 surveys are planned by the *FUSE* PI team, one to observe molecular hydrogen in diffuse environments, and another to measure the abundance and physical state of H_2 in translucent interstellar clouds, where significant dust extinction and gas-grain interaction occur.

Far-UV emission from active galactic nuclei and quasars: *FUSE* will be utilized to explore the far-UV spectra of bright AGNs and quasars. Among the important questions to be addressed are the energy sources in AGNs and quasars, the ionization state of the intergalactic medium, the ionization and kinematics of halo gas, and the composition of intergalactic clouds.

Hot star winds: *FUSE* will provide information on a number of species arising in the rapid winds from hot stars. Among the important questions to be addressed by *FUSE* are the occurrence and importance of the O VI and S VI ions in stellar winds; wind physical conditions derived from the ratio of ground-state and excited lines (as in C III λ977 as compared with C III λ1176); and the effects of galactic metallicity on the winds and mass-loss rates.

Cool star emission lines: Many important lines arising in cool-star chromospheres and coronae are observable in the far-ultraviolet, and *FUSE* will provide the first broad opportunity (since *Copernicus*) to survey these features in a wide range of stars. Among the most important diagnostics to be employed are hydrogen Lyman-series lines (Ly-β, etc.), C

III (λ977), N II (λ 1085), and O VI ($\lambda\lambda$1032,1038), but other lines (e.g. S IV λ1073 and N III λ990) will also be useful.

Far-ultraviolet spectra of hot subdwarfs and white dwarfs: For stellar surface temperatures in excess of 25,000 K, the primary thermal continuum flux is emitted at wavelengths within the *FUSE* spectral region, making *FUSE* potentially more effective than either the *HST* or the *IUE* for diagnosing physical conditions (and in some cases compositions) of hot subdwarf stars and white dwarfs.

Planetary studies: *FUSE* will provide unique data on the composition and physical state of planetary atmospheres, as well as interplanetary and circumplanetary plasmas, by providing spectra in the far-ultraviolet region where many important ions and molecules are uniquely accessible. In this area, *FUSE* will also make important contributions to the study of stellar disks, which may be precursors to extrasolar planet formation.

In order to accomplish all of the science goals outlined above, it will be necessary to have good basic data on the observed species and their spectral transitions. We have polled the community of known or anticipated *FUSE* users in an effort to determine specifically which data are needed, resulting in the following recommendations for continued or future laboratory work:

ATOMIC DATA

N I: The weak atomic nitrogen lines near 1160Å are vital to the derivation of accurate N I column densities, because they are generally weak enough in diffuse clouds to avoid saturation. Current oscillator strengths (f-values) are from a combination of theory and empirical astronomical studies, and are uncertain.

O I: Atomic oxygen has several multiplets below 1000Å, whose oscillator strengths are weak enough for the lines to be unsaturated in many cases, but accurate and reliable f-values are crucial. One of the most important applications will be the use of O I as a tracer of H I in studies of the D/H ratio.

Si II: No reliable *f*-values exist, either from theory or observation, for the lines at 1020 and 989Å; improvements are needed also for the basic data on the longer-UV transitions at 1526 and 1304Å.

Si IV: Here it is the wavelengths, not the *f*-values, that are in need of better data. The separation of lines in doublets such as this one can place important constraints on the cosmological evolution of physical constants, and telescopic accuracies for measuring line separations are now better than the accuracy of the lab data. (Better separations for other doublets such as Mg II, Al III, and C IV would also be helpful in this regard.)

Mn II: A large suite of lines arising from the ground electronic state of Mn II overlaps the *HST* and *FUSE* wavelength regions, but the current *f*-values are either theoretical or astrophysical. No good laboratory data exist.

Fe II, Fe III: The only astronomically accessible line of Fe III lies at 1122Å, and a number of useful Fe II lines also lie below the *HST* and *IUE* short-wavelength cut-off. The oscillator strengths for these lines (especially Fe III λ1122) are not well known, and need to be improved.

MOLECULAR DATA

CO: Carbon monoxide is the second most abundant molecule in interstellar space (after H_2), and is accessible through its infrared (vibrational) and millimeter-wave (rotational) spectra. Because CO has longer-wavelength UV electronic transitions accessible to the *HST*, *FUSE* is not the only instrument that can be used to measure CO abundances and physical states. But there are several CO electronic transitions within the *FUSE* bandpass, and these bands will be very useful diagnostics of chemical and physical conditions and will also help in extending the empirical CO/H_2 ratio into denser regimes than have been previously measured. At present there are large uncertainties in the oscillator strengths of the B-X, C-X, and E-X bands of CO which *FUSE* will observe whenever it is observing H_2. These bands include both strong and weak transitions which can be useful over a wide range of saturation (see Morton and Noreau 1994).

N_2: There are three sets of *f*-values (Lawrence *et al.* 1968; Carter 1972; Stark *et al.* 1992) for the bands of this important species, whose electronic transitions lie between 900 and 1000Å, and the three do not agree. *FUSE* has a chance to detect N_2 for the first time in interstellar space, but the *f*-value discrepancy needs to be resolved if we are to interpret the data correctly.

It is likely that basic spectroscopic data will be needed for additional species as the *FUSE* mission probes the universe at far-ultraviolet wavelengths. It is incumbent upon NASA to continue supporting programs to develop the background data necessary to interpret the vast amounts of data coming from space astrophysics missions such as *FUSE*.

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