Far Ultraviolet Astronomy and *Origins*: The Far Ultraviolet Spectroscopic Explorer (FUSE) Mission

Warren Moos, Kenneth Sembach, and Luciana Bianchi
Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218

Abstract. FUSE, a PI-class NASA astronomy mission, will explore the Universe through high-resolution spectroscopy (R = 24,000-30,000) at far ultraviolet wavelengths (905--1195 Å), to address fundamental questions related to the origin of the Universe. FUSE is scheduled as a three year mission within the NASA *Origins* program.

Keywords: abundances, atoms, dust, ISM, ultraviolet spectroscopy

1. Mission Overview

The Far Ultraviolet Spectroscopic Explorer (FUSE) mission will access the rich spectral region covering 905--1195 Å with a resolving power of ~1 part in 30,000. FUSE will extend NASA's ultraviolet spectroscopic capability from the *Space Telescope Imaging Spectrograph* cutoff at 1150 Å down to the Lyman limit at 912 Å, below which absorption by interstellar atomic hydrogen severely limits the usefulness of astronomical observations. In the fall of 1998, NASA will launch FUSE into an 800 km circular orbit for a three year mission. The satellite consists of four co-aligned telescopes/spectrographs mounted on a three axis stabilized spacecraft with arcsecond pointing capability. The satellite will be operated from the Homewood Campus of the Johns Hopkins University.

The space agencies of Canada and France are partners with NASA in the development and the future operations of the FUSE mission and will share in the observing time. As a PI class mission, NASA has placed the responsibility for mission development, including schedule and cost control, directly on the scientific community. The FUSE Science Team, listed in Table 1, has developed several comprehensive scientific objectives for the mission which are described briefly below. A Guest Investigator Program is planned.

Table 1: The FUSE Science Team

Warren Moos (PI)	The Johns Hopkins University
Webster Cash	The University of Colorado - Boulder
Lennox Cowie	The University of Hawaii
Arthur Davidsen	The Johns Hopkins University
Andrea Dupree	Harvard Smithsonian Center for Astrophysics
Paul Feldman	The Johns Hopkins University
Scott Friedman	The Johns Hopkins University

James Green	The University of Colorado - Boulder
Richard Green	Kitt Peak National Observatory
Cecile Gry	Laboratoire d’Astronomie Spatiale, Marseilles
John Hutchings	Dominion Astrophysical Observatory
Edward Jenkins	Princeton University
Jeffrey Linsky	The University of Colorado - Boulder
Roger Malina	The University of California - Berkeley
Andrew Michalitsianos	NASA/Goddard Space Flight Center
Blair Savage	The University of Wisconsin - Madison
Michael Shull	The University of Colorado - Boulder
Oswald Siegmund	The University of California - Berkeley
George Sonneborn	NASA/Goddard Space Flight Center
Theodore Snow	The University of Colorado - Boulder
Alfred Vidal-Madjar	Institute d’Astrophysique, Paris
Allan Willis	University College, London
Bruce Woodgate	NASA/Goddard Space Flight Center
Donald York	The University of Chicago

Other participants in the PI science include the FUSE Instrument and Operations Teams at The Johns Hopkins University, The University of Colorado, and The University of California.

2. Far UV Spectroscopy: An Unexplored Frontier

The FUSE wavelength region (905--1195 Å) is largely unexplored. In the 1970s, the *Copernicus* mission opened the far ultraviolet Universe by obtaining spectra of bright, hot stars within ~1 kpc of the Sun. Two telescopes, the *Hopkins Ultraviolet Telescope* (HUT) and the *Orbiting Retrievable Far and Extreme Ultraviolet Spectrometers* (ORFEUS), flown on Shuttle missions in the 1990s have also provided brief glimpses into the FUSE wavelength range. FUSE will be able to observe sources more than 10,000 times fainter than *Copernicus* at a resolution many times better than that obtainable with either HUT or ORFEUS. This increase in sensitivity will enable FUSE to explore the outer reaches of the Milky Way. It also makes it possible to use quasars and active galactic nuclei as continuum sources for absorption line studies of distant gas clouds.

The spectral window opened by FUSE will permit the study of many astrophysically important atoms, ions, and molecules which cannot be investigated otherwise. Most of this spectral window is not accessible with the *Hubble Space Telescope*, which has optics that transmit light only at wavelengths longer than 1150 Å. The full Lyman series of H I and D I (except for Ly-alpha at 1216 Å) will provide an unprecedented opportunity to make accurate measurements of D/H abundance ratios in a wide variety of astrophysical environments. O VI, an important diagnostic of astrophysical plasmas at temperatures approaching a million degrees, also appears in this wavelength region at 1032 Å and 1038 Å. The FUSE bandpass is extremely rich in spectral lines arising within the interstellar gas, the material from which stars and planets form. In addition to interstellar medium studies, observations in the FUV wavelength range provide opportunities to answer important questions about many types of astrophysical objects, such as AGNs and quasars, massive stars, supernovae, planetary nebulae, and the outer atmospheres of cool stars and planets.

3. FUSE and Origins

FUSE will make unique contributions to the *Origins* theme by studying the physical processes relevant to the origin and evolution of stars, galactic systems, and the Universe. The FUSE Science Team will address several key areas of science through comprehensive investigations.

Deuterium Abundances and the Origin of the Universe

One of the fundamental questions in astronomy that remains to be answered conclusively is whether the standard Big Bang model (or variant thereof) provides an acceptable description of the origin and evolution of the Universe and, if so, whether the Universe is open or closed. A critical test for the Big Bang paradigm can be provided by measuring the abundances of light elements and their isotopes at different places in the Universe and checking to see whether the measured values are consistent with Big Bang nucleosynthesis and the subsequent chemical evolution of the Universe. One such isotope is deuterium, which is created during the conversion of protons into helium nuclei. It is a sensitive indicator of the baryonic density in the hot, early Universe. Deuterium locked into stars during their formation is destroyed by stellar nucleosynthesis, and therefore it is believed that the net abundance of deuterium in the Universe should decrease with time.

- The FUSE Science Team will obtain absorption line measurements of deuterium abundances in a wide range of Galactic environments having varying degrees of metallicity and different evolutionary histories.

- Regions to be explored include the local interstellar medium, distant gas clouds in the disk of the Galaxy, the Milky Way halo, and low redshift ($z < 0.3$) intergalactic clouds and galactic halos.

- These measurements will be used to test current theories of the chemical evolution of galaxies and the resulting degree of astration of deuterium.

- Since heavy element (eg., O, N, S, Fe) production is intimately linked to the rate and degree of chemical processing within galaxies, these studies will include estimates of the abundances of these important elements whenever possible.

Hot Gas and the Origins of Galaxies

In the last two decades, considerable efforts have been made to understand the distribution, ionization, and kinematics of hot gas within the Milky Way. The two principal means by which this has been accomplished are X-ray emission observations and ultraviolet absorption line studies with Copernicus, IUE, and the HST. X-ray studies have focused primarily on the hot gas emission located within the Local Bubble or on isolated hotspots where there is enhanced emission associated with known structures, such as the North Polar Spur or supershells in the Large Magellanic Cloud. Observations of O VI absorption have also been recorded for local material, but it is only through measurements of O VI absorption toward distant background sources that it will be possible to fully characterize the widespread distribution of hot gas within the Milky Way.

- The FUSE Science Team will conduct a survey of O VI absorption in the Milky Way disk and halo to determine the physical properties and distribution of hot gas within the Galaxy.

- Halo stars and AGN/QSOs will be used as background sources so that entire paths through the halo can be explored.

- A number of pointings toward stars in the Magellanic Clouds will be used to determine the relationship of O VI absorption and the X-ray properties of known shells and supershells in these galaxies.

- This program will also characterize the extent, distribution, and kinematics of O VI in the Galactic disk, which will lead to a better understanding of how matter and energy are transferred within the Galaxy.

Molecular Gas and the Origins of Stars

Compared to the atomic and ionized interstellar medium, there is relatively little known about the molecular constituent, which comprises most of the interstellar mass. Most of this information has come through observations of CO emission at millimeter wavelengths and H_2 vibrational level emission in the infrared. The *Copernicus* satellite provided an initial glimpse directly into the electronic transitions of H_2 within the solar neighborhood along relatively diffuse sight lines. Measurements of H_2 absorption in the ultraviolet provide information about the formation and destruction of molecules in environments that are not deeply embedded in molecular clouds. This information is difficult to obtain from longer wavelength measurements alone. In particular, observations of the electro-vibrational transitions of H_2 and CO in the ultraviolet provide important information about the rotational ladder populations of these molecules, their radiative pumping and collisional de-excitation, and the intensity of the UV radiation field.

- FUSE will greatly extend the pioneering H_2 work started with *Copernicus* by probing distant clouds.

- FUSE will observe several magnitudes deeper into clouds with large far ultraviolet extinction.

- Sight lines in the diffuse ISM will be explored to understand the rotational distribution of H_2, the physical properties of the molecular gas, and the UV radiation field.
- Sight lines piercing translucent clouds will be observed to determine the relationships between H_2, dust grain composition, and the ultraviolet extinction of starlight.

4. Additional FUSE Science Objectives

In addition to the three unique science areas outlined above, FUSE will make significant contributions to other areas of astronomy, including:

- Searches for the observational signature of the hot intergalactic medium, to determine how the Universe evolved at high redshifts.

- Investigations of highly ionized gases associated with active galactic nuclei, to provide insight into the mechanisms for ionizing gas clouds near massive black holes.

- Studies of nova and supernova explosions and their remnants, to test theories of heavy element nucleosynthesis and the evolution of stars.

- Studies of the hottest atmospheric layers of stars, to provide information about mass loss through stellar winds (hot stars) and the structure of stellar coronae (cool stars).

- Investigations of jets and circumstellar disks, to understand the properties of stars in early stages of their evolution.

- Determinations of the abundances of primordial gases in comets and planetary atmospheres, to understand the origin and evolution of the solar system.

5. The FUSE Satellite

The FUSE satellite is composed of the spacecraft and the scientific instrument. The spacecraft has a mass of 580 kg and is three-axis stabilized. With the Fine Error Sensor (FES) on the instrument, the spacecraft will routinely achieve a pointing capability of 0.5 arcsec in pitch and yaw.

To eliminate large reflection losses by additional optical elements, the instrument has four co-aligned telescopes (~39 cm x 35 cm clear aperture) rather than the conventional single optic (Figure 1). The light from the four optical channels is dispersed by four spherical, aberration-corrected holographic diffraction gratings, and recorded by two delay-line microchannel plate detectors. Two channels with SiC coatings cover the range 905--1100 Å and two channels with LiF coatings cover the range 1000--1195 Å.

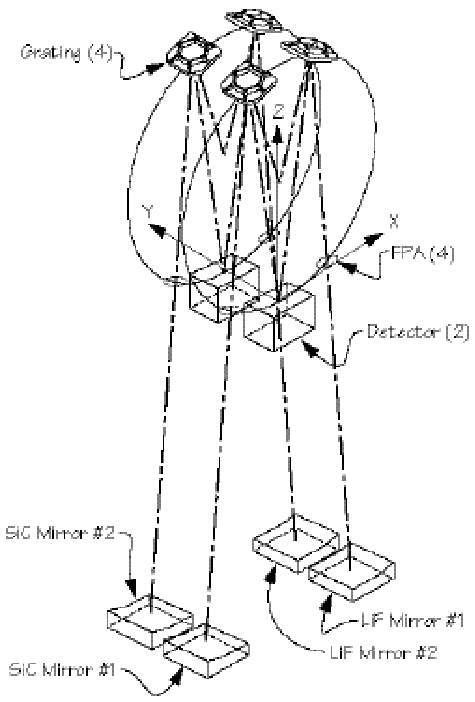

Figure: Schematic of the FUSE optical system

Actuators on the mirror mountings will keep the focus to 90% encircled energy within 1.5 arcsec. The FES has a 21 arcmin square field of view and will be used to identify the pointing location and to stabilize the spacecraft pointing. The basic instrument parameters are summarized in Table 2.

Table 2: Instrument Parameters

Wavelength Coverage	905-1195Å
Mirrors	Four off axis parabolas
Effective area	20-80 cm^2
PSF	1.5" (90% encircled energy)
Science Apertures	1.25" x 20", 4" x 20", 30" x 30"
Spectrograph	Rowland Circle (1652mm)
Spectral resolution	lambda/Delta lambda = 24,000 - 30,000
Detectors	Double delay line MCP
FES Field of View	21’ x 21’
Total Length	Four meters
Mass	780 kg

6. The FUSE Mission

The Johns Hopkins University (Dr. H. Warren Moos, PI) is responsible for developing the overall mission, in collaboration with: The University of Colorado, The University of California (Berkeley), JHU/Applied Physics Laboratory, The Canadian Space Agency, Centre National d’Etudes Spatiales (France), Goddard Space Flight Center, Orbital Sciences Corporation, Swales Aerospace, Interface and Control Systems, Inc., and AlliedSignal, Inc.

More information about the FUSE Project can be obtained on the FUSE web homepage: http://fuse.pha.jhu.edu/. Information about the FUSE Guest Investigator program is available from Dr. George Sonneborn, the GSFC FUSE Project Scientist (sonneborn@stars.gsfc.nasa.gov).