CURRENT NASA STUDIES FOR A FAR-ULTRAVIOLET SPECTROGRAPHIC EXPLORER (FUSE)

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ABSTRACT

This report summarizes the current status of planning by a NASA science working group for the proposed Far-Ultraviolet Spectrographic Explorer (FUSE). These plans are still far from complete and may be modified greatly before a final report is completed, but they envision a satellite to obtain spectra with resolutions ($\lambda/\Delta \lambda$) between $1 \times 10^5$ and 100 in the spectral regions 912 Å to somewhat longer than 1216 Å and 100–912 Å. This report summarizes the important new scientific problems that can be studied by FUSE, but cannot be addressed by IUE or ST, which are sensitive only to wavelengths longward of 1200 Å. We also describe two new optical designs — a grazing incidence echelle and a hybrid echelle — to accomplish these scientific goals with high throughput, large simultaneous spectral range, and low background photon-counting statistics. We envision FUSE to be an international collaborative satellite operated in a guest investigator mode like IUE.

Keywords: Extreme Ultraviolet Spectroscopy, Grazing – Incidence Optics, Interstellar Medium, Galactic Astronomy, Extragalactic Astronomy, Cool Stars, Hot Stars, Solar System Astronomy

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1. INTRODUCTION

The clear success of IUE as demonstrated by the important scientific results reported at this and previous meetings has prompted many people to commence thinking about future missions that would further expand the horizons of ultraviolet astronomy. The Space Telescope will accomplish this purpose for many but not all problems that can be addressed by observations at wavelengths longward of about 1200 Å. However, a great many crucial problems in astrophysics can only be addressed by spectroscopy at shorter wavelengths. This need has prompted NASA to form a science working group to investigate the feasibility of a Far-Ultraviolet Spectrographic Explorer (FUSE) satellite. The following preliminary report summarizes the present views of the group, consisting of the authors of this paper, but these views may change before a final report is written, and this paper does not contain any plans or policies adopted by NASA.

The primary motivation for FUSE comes from the fact that the techniques of ultraviolet spectroscopy and the successful operational strategy of IUE can be used to study a whole new set of problems and revolutionise our understanding of older problems when we have a satellite capable of observing at wavelengths below Lyman alpha. IUE's success can be ascribed to the power of high and low resolution spectroscopy with large simultaneous wavelength coverage, a guest investigator mode of operations involving large numbers of astronomers, real time operations, rapid access to the data by the original observers and open data archives after six months, and especially to international collaboration in all phases of the IUPE program that has brought together the best talent from both sides of the Atlantic. From the very beginning, the FUSE Science Working Group has urged that international collaboration and the other positive aspects of IUPE be essential components of the FUSE mission.

2. SPECTROSCOPY SHORTWARD OF LYMAN ALPHA

2.1 The 912–1216 Å Spectral Region

The hydrogen Lyman continuum edge at 912 Å provides a natural division between what we here call the far ultraviolet (912–1216 Å) and the extreme
ultraviolet (\(\lambda < 912 \text{ Å} \)), since the Lyman continuum severely limits the number of objects that can be detected. The Lyman continuum edge does not, however, correspond to any fundamental instrumental consideration as we shall see. Before addressing the science that can be accomplished by spectroscopy in the far ultraviolet, we summarize the important spectroscopic features present in this wavelength interval that are useful in studying a wide range of problems.

(1) Molecular hydrogen (H\(_2\)) is the dominant constituent of cold clouds in the interstellar medium. The two important electronic bands of H\(_2\) are the Lyman band at \(\lambda < 1120 \text{ Å} \) and the Werner band at \(\lambda < 1008 \text{ Å} \), although in a few objects fluorescent H\(_2\) is seen at wavelengths up to 1600 Å and the weak quadrupole vibration-rotation lines are occasionally observed in the near infrared.

(2) The strongest lines of atomic hydrogen (H I) are the resonant Lyman lines \(L_{\alpha} (1216 \text{ Å}), L_\beta (1025 \text{ Å}), L_\gamma (972 \text{ Å}), L_\delta (950 \text{ Å})\), and higher members extending to the continuum limit at 912 Å.

(3) The resonance lines of deuterium (D I) are located slightly shortward of the hydrogen Lyman lines.

(4) The molecule HD has electronic bands only in the far ultraviolet at \(\lambda < 1130 \text{ Å} \) with the strongest lines near 1050 Å.

(5) There are many important ions for which the only lines or the strongest lines lie in the far ultraviolet. These include C III (977,1175 Å), N I (1200 Å), N II (916,1084,1085 Å), N III (991 Å), O VI (1032,1038 Å), A I (1048,1066 Å), P IV (951 Å), P V (1118,1128 Å), S III (1012,1190 Å), S IV (1062 Å), and S VI (940 Å). Of special importance are the O VI, P V and S VI ions that are formed at \(3 \times 10^5 \text{ K} \), a higher temperature than any line observable by TUE, and C III which may be the dominant ionization stage in many astrophysical plasmas. However, the 912-1216 Å spectral range, like the TUE range, contains no strong lines indicative of hot plasma (\(T > 3 \times 10^5 \text{ K} \)).

(6) As a result of its rich spectrum of strong lines, the 912-1216 Å spectral range can be used to study many ionization stages simultaneously, including N I-III, P II-V, S III-VI, and C II-I-IV. This is important for studying the ionization equilibria of astrophysical plasmas and for abundance analyses since a given spectrum will often contain all the important ionization stages.

(7) There are a number of important density sensitive line ratios available like C III 977 Å/1175 Å.

2.2 The 100-912 Å Spectral Range

Below 912 Å a different set of spectral features becomes important.

(1) The hydrogen Lyman continuum is important because one must see through the hydrogen interstellar absorption to detect sources outside the solar system. Absorption in the He I (\(\lambda < 504 \text{ Å} \)) and He II (\(\lambda < 227 \text{ Å} \)) continua can also be important.

(2) All of the strong lines of helium, the second most abundant atom in the universe, lie in this spectral range. The He I resonance lines (584, 537, 522 Å, ...) lie in a series extending to the continuum edge of 504 Å, and the He II resonance lines (304,256,243 Å, ...) lie in another series extending to their continuum edge at 227 Å.

(3) Voyager observations of the Io torus (Ref. 1) show many strong lines of intermediate stages of ionization including O II (539,834 Å), O III (703,835 Å), and S IV (657,745,816 Å).

(4) A resonant line of the abundant species Ne I lies at 736 Å.

(5) The most important features in this spectral range are probably the strong lines of highly ionized plasma indicative of temperatures (assuming that the plasma is thermal) of \(6 \times 10^5 - 3 \times 10^7 \text{ K} \). Some of these important lines are listed in Table 1, together with the temperatures corresponding to their maximum abundance (Ref. 2). It is the presence of these high temperature lines that makes this spectral range unique for ultraviolet spectroscopy.

<table>
<thead>
<tr>
<th>Ion</th>
<th>(\log T)</th>
<th>Important Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne VII</td>
<td>5.8</td>
<td>465 Å</td>
</tr>
<tr>
<td>Ne VIII</td>
<td>5.9</td>
<td>770,780 Å</td>
</tr>
<tr>
<td>Mg X</td>
<td>6.1</td>
<td>610,625 Å</td>
</tr>
<tr>
<td>Fe XII</td>
<td>6.3</td>
<td>187 Å</td>
</tr>
<tr>
<td>Si XII</td>
<td>6.4</td>
<td>499,512 Å</td>
</tr>
<tr>
<td>Fe XV</td>
<td>6.5</td>
<td>284 Å</td>
</tr>
<tr>
<td>Fe XIV</td>
<td>6.6</td>
<td>335,361 Å</td>
</tr>
<tr>
<td>Fe XVIII</td>
<td>6.8</td>
<td>104 Å</td>
</tr>
<tr>
<td>Fe XIX</td>
<td>6.9</td>
<td>108 Å</td>
</tr>
<tr>
<td>Fe XX</td>
<td>7.0</td>
<td>121 Å</td>
</tr>
<tr>
<td>Fe XXI</td>
<td>7.2</td>
<td>108,138,150 Å</td>
</tr>
<tr>
<td>Fe XXIV</td>
<td>7.5</td>
<td>192,255 Å</td>
</tr>
</tbody>
</table>

3. IS THE SPECTRAL REGION BELOW 912 Å OBSERVABLE?

We summarize this topic because our understanding of the inhomogeneous density distribution of interstellar hydrogen in the local region of our galaxy is rapidly changing. Craddock et al. (Ref. 3) have computed the effective cross section of interstellar gas including the H I Lyman continuum, continua due to He I, He II, and the metals, and dust absorption. For the 504-912 Å region the dominant absorber is hydrogen, for which \(\tau_\lambda \sim (v/v_\infty)^{-3}\), but He I absorption is also important below 504 Å. In Table 2 we list the distances corresponding to unit optical depth (\(\tau_\lambda = 1\)) for different assumed interstellar neutral hydrogen densities, \(n_H\). This table illustrates how rapidly the UV horizon expands with decreasing \(n_H\) and \(\lambda\).

Bohlin, Savage, and Drake (Ref. 4) summarized the picture of the interstellar medium (ISM) as derived from Copernicus observations of hot stars lying between 60 and 2000 pc mainly in the galactic plane. They found that for all these lines of sight the mean density is \(n_H \approx 0.86 \text{ atoms cm}^{-3}\).
Table 2.

<table>
<thead>
<tr>
<th>λ</th>
<th>( n_{\text{H}}^{-1} ) cm(^{-3} )</th>
<th>( n_{\text{H}}^{-0.1} ) cm(^{-3} )</th>
<th>( n_{\text{H}}^{-0.01} ) cm(^{-3} )</th>
<th>( n_{\text{H}}^{-0.001} ) cm(^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>912 Å</td>
<td>0.05</td>
<td>0.5</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>500 Å</td>
<td>0.2</td>
<td>2</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>200 Å</td>
<td>1.5</td>
<td>15</td>
<td>150</td>
<td>1500</td>
</tr>
<tr>
<td>100 Å</td>
<td>10</td>
<td>100</td>
<td>1000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

but the mean density for those lines of sight with negligible H\(_2\) absorption (i.e., no clouds in the line of sight) is \( n_{\text{H}}^{-1} = 0.16 \) atoms cm\(^{-3} \). They also found that the ISM is extremely patchy with \( n_{\text{H}}^{-1} \) as low as \( 0.008 \) atoms cm\(^{-3} \) towards β CMa (206 pc) and e CMa (188 pc) in the Gum Nebula, but as large as 12 atoms cm\(^{-3} \) for stars embedded in clouds.

A somewhat different picture emerged from Copernicus observations of Lyman alpha absorption toward cool stars within 15 pc (Refs. 5, 6) and measurements of backscattered solar Lyman alpha and He I λ584 lines off of neutral interstellar gas flowing through the solar system (Refs. 7, 8). These data are consistent with a local interstellar density of \( n_{\text{H}}^{-1} = 0.10 \) atoms cm\(^{-3} \) and temperature of 5000 K. Thus the Sun is in a warm component of the ISM.

Very recently, Bruevender and Kondo (Ref. 9) summarized our present understanding of the local ISM based on the above data, IUE observations of Ly\(_2\) absorption towards five hot white dwarfs within 48 pc, Voyager EUV data, and an EUV rocket spectrum of the hot white dwarf He SMART 43 (65 pc) from which Malina et al. (Ref. 10) derived a hydrogen column density \( n_{\text{H}} \leq 2 \times 10^{17} \) cm\(^{-2} \) and \( n_{\text{H}} \leq 0.002 \) cm\(^{-3} \). They concluded that the Sun lies near the edge of a warm cloudlet with \( n_{\text{H}} \approx 0.1 \) cm\(^{-3} \). In the galactic center direction, the column density through the cloudlet is \( n_{\text{H}} \approx 1 - 2 \times 10^{19} \) cm\(^{-2} \), corresponding to 30-60 pc, but toward the antecenter (\( l = 180^\circ \)) and out of the plane the column densities are lower, \( n_{\text{H}} \approx 2 \times 10^{17} - 2 \times 10^{18} \) cm\(^{-2} \), corresponding to 0.6-6 pc. Beyond the local cloudlet and extending to at least 50 pc in most directions is hot interstellar gas with \( n_{\text{H}} \approx 0.001-0.01 \) atoms cm\(^{-3} \) and negligible opacity.

There are also unpublished 21 cm data obtained by Heiles (Ref. 11) that imply that for roughly 5% of the sky at high northern galactic latitudes, \( n_{\text{H}} \approx 4 \times 10^{19} \) cm\(^{-2} \) for lines of sight to outside of our galaxy. For these lines of sight \( t_{100} = 1 \), permitting observations of extragalactic sources. It is likely, however, that even lower column densities occur along some lines of sight, since the 21 cm data have an angular resolution of 5°. We summarize all the present data on lines of sight toward nearby stars in Fig. 1. These data are incomplete, but they clearly show that UV observations of many stars and at least a few extragalactic sources are possible, especially for an instrument that can observe down to 100 Å.

4. THE IMPORTANT SCIENTIFIC QUESTIONS THAT ARE DRIVING THE FUSE DESIGN

We summarize below some of the important scientific questions that can be addressed and, we hope, solved by a FUSE mission. We enumerate these questions because they call attention to the spectral features that should be observed and thus the spectral range and spectral resolution the FUSE design should attempt to accommodate. We point out, however, that an essential aspect of most space missions is the discovery of new phenomena unanticipated prior to launch. This should be especially true for FUSE since it will be studying objects at least 12 magnitudes fainter than those studied by Copernicus in the 912-1216 Å spectral range, while in the 100-912 Å spectral range FUSE will be the first spectroscopic mission. Thus it is extremely important that FUSE be a flexible instrument with a wide spectral range available for simultaneous observations. Below we list the scientific goals and the spectroscopic features needed. For clarity we determine from features at 100-912 Å and put in parentheses those features at 1216-1700 Å.

4.1 The Interstellar Medium

(1) The single most important ISM problem is to determine the physical properties (i.e., temperature, density, nonthermal velocities) of the different components of the ISM in our galaxy and in external galaxies. For example, the dark cold clouds can be studied best by observing the Lyman and Werner bands of H\(_2\) at \( 1 \times 10^5 \) resolution (see 6.1) in absorption toward hot stars. Similarly the warmer components of the ISM (H I regions ionized by ultraviolet photons in diffuse starlight, H II regions photoinized by specific stars, and H II regions on the cloud edges) can be studied by high resolution spectroscopy of the H I Lyman lines, H\(_2\), and such species as N I and N II. Interstellar shocks at \( 2 \times 10^4 - 1 \times 10^5 \) K can be studied by the High Resolution Spectrograph on Space Telescope using lines of (C II), (Si IV), and (C IV), but the evaporating interfaces at the edge of the hot component of the ISM contain \( 1 \times 10^6 - 1 \times 10^6 \) K plasma and can be studied using lines of O VI, S VI, (N V), and others. Finally, the hot component of the ISM, which may occupy 75% of the volume of our galaxy and lie at temperatures of \( 5 \times 10^5 - 3 \times 10^6 \) K can only be studied by observing high temperature lines (i.e., Mg X, Si XII, Fe XII-XVI) at moderate resolution \( \lambda / \Delta \lambda = 2-4 \times 10^4 \).

(2) An accurate determination of the primordial deuterium/hydrogen ratio would be of great value in determining the parameter \( Q_0 \) needed in cosmology theories. The D/H ratio along different lines of sight can be determined from the Lyman line D I/H I column density ratios or from the HD/H\(_2\) column density ratios in lines of sight through dark clouds. Lines of sight through the galactic halo (using quasars, Seyferts, or globular clusters as external sources) or possible intergalactic clouds should be especially useful in estimating the primordial D/H ratio. Along other lines of sight, departures from the primordial D/H ratio are possible depending on the
Fig. 1. A summary of measured interstellar hydrogen column densities \( N_H \) and corresponding hydrogen number densities \( n_H \) for all observed stars within 100 pc and more distant stars with \( N_H \leq 10^{20} \) cm\(^{-2}\). Also listed are the wavelengths corresponding to monochromatic optical depth unity for given column densities, and an estimate of the total number of stars within specific distances. The number of stars measured to date is far too incomplete a sample. The line marked 32 corresponds to the column density upper limit for roughly 5% of the sky at northern high galactic latitudes to outside of our galaxy, estimated by Heiles (Ref. 11). The stars included are: (1) α Cen A, (2) ε Eri, (3) ε Ind, (4) α CMi, (5) β Gem, (6) α Boo, (7) α Aur, (8) α Tau, (9) α Leo, (10) α Eri, (11) α Gru, (12) HH 1099, (13) η CMA, (14) G191 B2B, (15) HE 43, (16) Feige 24, (17) α Vir, (18) λ Sco, (19) ν Sco, (20) ε CMA, (21) η CMA, (22) γ Vel, (23) ζ Pup, (24) μ Col, (25) η CMA, (26) 3C 287, (27) 3C 286, (28) σ Sgr, (29) α Pav, (30) β Cen, (31) β Lyr, (32) α CMA, (33) α Lyr, (35) α Aql, (36) ζ Gem, and (37) α Cru.

roles that stars play as sources and sinks of deuterium and on how well the interstellar medium is mixed. The determination of D/H in external galaxies and their halos as a function of distance would be very valuable.

(3) Castor, McCray, and Weaver (Ref. 12) predicted that "bubbles" in the ISM should be created when the massive winds of O and WR stars push away the ambient ISM. The existence of these bubbles could be verified by O VI and C III observations with FUSE, and the densities behind the wind-ISM shock fronts could be determined from the N II λ1084/λ1085 column density ratio and absorption lines out of rotationally excited H\(_2\) levels.

(4) The masses of the gaseous components of galaxies are now routinely estimated based on microwave observations of \(^{12}\)CO, but such measurements require knowledge of the H\(_2\)/CO ratio since the gas is mainly hydrogen. FUSE can measure the H\(_2\)/CO ratio directly since lines of both molecules are present in the 912-1216 Å spectral range.

(5) We would like to better understand the chemistry of dark clouds by determining the density, temperature, ultraviolet radiation fields, and heating rates in these clouds. Compositional observations of H\(_2\) and the ultraviolet continua of hot stars near the clouds are essential for addressing these problems. Also the HD/H\(_2\) abundance ratio can be used to infer the cosmic ray heating rate and to correlate it with γ-ray observations from HEAO-3 and COS-B.

(6) Spatially-resolved spectra of supernova remnants can determine the temperatures and densities in the shock fronts at the SN-ISM interface (e.g., EUV lines of Fe XII-Fe XVI) and in the cooling plasma behind these shocks (e.g., (C II), C III, O VI, N V, and (C IV)).

(7) Studies of the interstellar absorption cores of the higher Lyman lines and the shape of the EUV continua of hot white dwarfs along many lines of sight will probe the density distribution of the interstellar medium and the local cloudlet in which the Sun is embedded.

(8) The other observations have shown that Herbig-Haro objects have very bright ultraviolet continua and emission lines indicating that these presumably pre-main sequence objects have extensive amounts of hot plasma. Just how hot these plasmas are and the nature of the heating mechanisms are uncertain, but observations of their 912-1200 Å continua and the O VI and Fe XII-Fe XVI lines may answer these questions.
(9) Finally, measurements of extinction in the 912-1200 Å region and the EUV continuum toward hot stars should be useful probes of the sizes and constituents of small grains in the ISM and in circumstellar envelopes.

4.2 Material in the Outer Regions of Galaxies (Galactic Halos)

Spitzer (Ref. 13) predicted in 1956 that very hot material should exist above the galactic plane, but direct evidence for such material was lacking until Stang and de Boer (Ref. 16) discovered blue-shifted (C IV) and (Si IV) absorption features in lines of sight toward 0 stars in the Magellanic clouds. FUSE is optimally suited to exploiting this important TUE discovery by addressing the following questions:

(1) What is the distribution of halo gas as a function of distance from the galactic center and above the galactic plane, and what is the physical state (temperature and density) of this gas? Also what is the kinematic state of this halo gas; is it corotating with the rest of the galaxy, outflowing, or infalling? These questions can be answered by moderate resolution spectra (\(\lambda/\Delta\lambda \sim 2 \times 10^4\)) of the P V, S VI, and O VI absorption lines formed at 3 \(\times 10^5\) K, and the high temperature lines of Fe XII - Fe XVI near 100 Å along those lines of sight toward hot stars or galactic nuclei where \(N_{HI} \leq 4 \times 10^{12}\) cm\(^{-2}\). In order to determine the physical state of the gas, one must determine whether the degree of ionization is thermal or whether the gas is photoionized, and whether the ionization equilibrium is steady-state or time dependent.

(2) What is the chemical composition of the halo gas? This is an especially important question as the halo gas could be nearly primordial. Since the 912-1216 Å region contains the higher Lyman lines that are not saturated, spectra in this region can be used to obtain the D/H, O/H, and N/H ratios directly. A related question is whether dust grains and H\(_2\) exist in the halo.

(3) What is the origin of the halo gas? According to the galactic fountain model (Ref. 15), hot plasma is ejected from the galactic plane by interstellar shocks and bubbles. This gas rises to high distances above the plane and then cools radiatively as it falls back toward the plane. This model can be tested by radial velocity measurements for spectral lines with different formation temperatures along many lines of sight. Available background targets are high galactic latitude B stars, hot globular clusters, and any detectable external object.

(4) Presumably external galaxies also possess hot halos. These can be studied with the same techniques as previously described using sources internal to the galaxy (the galactic nucleus and OB stars) or more distant sources such as quasars, Markarian galaxies, or Zwicky compact galaxies. Can absorption in the extended halos of galaxies explain the complex quasar absorption line spectra at \(z < z_{em}\) and could these halos be sufficiently massive to close the universe?

4.3 Extragalactic Astronomy

In view of our presently poor understanding of hydrogen column densities (\(N_{HI}\)) along lines of sight to the edge of our galaxy, we cannot estimate the number of galaxies that could be observed in the EUV. If a number of galaxies can be detected at 100-500 Å, then extragalactic astronomy may provide some of the most spectacular discoveries of the FUSE mission. Even if only a few can be studied in the EUV, however, the 912-1200 Å region will provide many valuable insights.

(1) What is the initial mass function in galaxies, such as irregulars and Markarian galaxies, where extensive star formation is now in progress? The way to answer this question is by observing the young O stars, either singly in the nearby galaxies or in terms of their contribution to the integrated flux of the galaxy. The 912-1200 Å continuum and the EUV continuum near 100 Å are produced mainly by these stars.

(2) What is the energy distribution of active galactic nuclei? While the ultraviolet and X-ray continua for a number of these objects are known, the flux distributions in the EUV are unknown and cannot be interpolated from fluxes at larger and shorter wavelengths. Measurements of the continuum slopes in both the 912-1200 Å region and near 100 Å should provide direct information on the central energy sources that emit synchrotron or synchrotron-inverse Compton radiation.

(3) What are the properties of the local intergalactic medium? Since this gas could be highly ionized, we do not expect significant absorption in the hydrogen Lyman lines and continuum. However, the He II resonant line (304 Å) and continuum (\(\lambda < 227\) Å) could have appreciable column densities. FUSE can be used to search for absorption troughs extending from \(\lambda_0 = 304\) Å or 227 Å toward (1 + \(z_{em}\))\(\lambda_0\) in low resolution spectra of galaxies at \(z_{em}\) up to about 5.

(4) What are the physical properties of the hot gas in Seyfert and other active galactic nuclei? For this problem the useful diagnostics are emission line profiles of O VI and lines of Fe XII - Fe XVI near 100 Å.

4.4 Cool Stars

TUE and HEAO-2 revolutionized the study of cool stars by providing evidence for hot coronae and measuring the physical properties and outflow velocities of stellar chromospheres and transition regions at temperatures up to 2\(\times 10^5\) K. Using the powerful techniques of ultraviolet spectroscopy, FUSE can extend these studies to the analysis of higher temperature plasmas and provide new tools for addressing other problems.

(1) What are the properties of the hot coronal gas that exists around all cool stars, except the luminous K and M stars? There are no permitted or strong interstellar lines formed at \(T > 3 \times 10^5\) K available at \(\lambda > 912\) Å, but as shown in Table 2 there are many strong lines formed at \(T = 6 \times 10^4\) \(\times 10^6\) K available in the 100-912 Å spectral range. Measurements of line fluxes and certain line flux ratios provide many useful diagnostics of plasma temperature and emission measure distributions as well as coronal densities. Also, a spectral resolution of \(\lambda/\Delta\lambda = 20,000\) in the 100-912 Å range could measure transition region and coronal expansion and circulation velocities from line shifts and asymmetries. In principle, soft X-ray observations can provide similar information, but soft
X-ray high resolution spectroscopy is presently feasible only with very low throughput. Repeated observations of the same stars can study the inhomogeneous distribution of emitting structures across the stellar surface from rotational modulation of bright active regions.

(2) Do coronae exist around some stars with temperatures intermediate between those observable by UVE (T < 2x10^5 K) and by HEAO-2 (T > 1x10^6 K)? Candidate stars for such coronae include the later K giants, some premain sequence stars, and the hybrid stars (Ref. 16). The most useful emission lines to search for are the O VI, λλ1032,1038 resonance lines.

(3) A number of A and B-type stars, such as Vega and Sirius A, emit soft X-rays, but as yet no emission features have been detected from the intermediate temperature layers that must exist between the photosphere and corona. The bright photosphere in the ultraviolet makes such measurements difficult, but the photoionization edges of C I at 1100 Å and H I at 912 Å should provide a dark background against which even faint emission lines formed above the photosphere may appear at reasonable contrast. The O VI resonance lines may be the best lines to search for in these stars.

(4) What is the global energy balance in different types of cool stars? In particular, how much heating occurs at different layers (temperatures) in a stellar atmosphere, in different atmospheric structures, and in transient events as a function of time. In the past one could observe only a limited temperature range in a stellar atmosphere using for example UVE or HEAO-2. FUSE, on the other hand, will permit simultaneous spectroscopic measurements of lines formed at all relevant temperatures from 5x10^3 K (O I, C I, S I) to T > 10^7 K in the EUV. This is an incredibly powerful diagnostic tool for cool stars as well as for the wide range of astronomical objects that contain both cool and hot plasma.

(5) The very stable velocity fiducials provided by the interstellar Lyman lines in absorption against the chromospheric Lyman emission lines should facilitate a number of important measurements. For example, the monitoring of spectroscopic binary stars should permit one to identify which star is the dominant emitter from the changing Lyman line asymmetries. Also, with such data one should be able to estimate systematic motions (winds, infall), watch active regions rotate on and off the stellar disk, and perhaps even measure stellar oscillations from the variable Doppler signal.

(6) Finally, it may be feasible to measure the mass loss from M supergiants as a function of time by observing H2 emission shells that are fluoresced by the dilute ultraviolet radiation field in the ISM.

4.5 Hot Stars

Copernicus, IUE, and HEAO-2 have also revolutionized our understanding of the expanding outer atmospheres of hot stars, but the observations with these satellites were unable to answer many questions, and they raised a number of new questions. Some of these are questions that FUSE could answer:

(1) What is the precise reason why there is so much O VI in the warm winds of these stars? One possible explanation is Auger ionization due to soft X-rays. In a few stars with low interstellar column densities, such as ζ Pup and γ2 Vel, it may be possible to answer this question directly by simultaneous measurements of the amount of hot plasma (emission lines near 100 Å) and the O VI column density. An alternative means is to determine the ionization equilibria from measurements of the column densities for many stages of ionization particularly of the same element. The 912-1200 Å region is ideal for this purpose since it permits simultaneous observations of P II, III, IV, and V, and S II, III, IV, and VI, in addition to other useful species such as C III and O VI. The comparison of C III λ977 with the multiplet at λλ176 is a good diagnostic of wind densities, since the latter arises from a metastable level while the former is a resonance line.

(2) What are the dynamics and time variability of O and Wolf-Rayet star winds, and what are the acceleration mechanisms for these winds? These questions can be addressed by studying the P Cygni line profiles and their time variations for the O VI, C III, (C IV), and (N V) resonance lines simultaneously.

(3) What are the differences between the winds of hot stars in our galaxy and those in the many external galaxies that FUSE should be able to study at a resolution of λ/Δλ = 2000. One might see winds with different velocity laws and mass loss rates in galaxies with different metal abundances.

(4) The 100-912 Å spectral range should be very useful in studying hot white dwarfs, which are abundant in the solar neighborhood. The continuum energy distribution in this spectral range will lead to the first accurate measurements of effective temperatures for T_eff > 2x10^8 K; such data should allow the theoreticians to assess the role of neutrino core cooling during stages of evolution immediately prior to the formation of the white dwarf and to distinguish among different possible white dwarf models. Also direct measurements of the He/H surface abundance ratio from measurements of the He II discontinuity at 227 Å and the He II λ304 absorption line (resolution of 2x10^6 needed to separate stellar from interstellar absorption) will provide critical information on the gravitational settling of helium in white dwarf atmospheres and the time scale for this phenomenon.

(5) Naturally many binary systems containing hot stars or hot disk material could be studied by FUSE. One unique contribution that FUSE could make to these studies is to measure the shape of the EUV continuum flux in cataclysmic variables during outburst, where IUE and HEAO-2 observations indicate that the peak flux should occur. One proposed energy source for outbursts in cataclysmic variables is nuclear burning at the surface of the white dwarf in these systems when sufficient matter has been accreted.

4.6 Solar System Objects

The full 100-1200 Å spectral range is accessible for solar system research since Lyman continuum absorption is insignificant even at 912 Å. FUSE
should be an instrument superior to the ultraviolet spectrometer on Voyager as a consequence of the additional 100-500 Å spectral range and far greater sensitivity at wavelengths longward of 500 Å. Several important problems for FUSE are:

1. What are the physical conditions in the Io torus surrounding Jupiter as a function of time? Voyager detected lines of S II, S III, and S IV between 657 and 1256 Å, but will observations at higher resolution (say λ/Δλ = 2000) and at shorter wavelengths (λ < 500 Å) reveal more highly ionized species? Time resolution is required to study nonsteady state ionization equilibrium effects. Spatial resolution along the spectrograph slit is also essential for this program. One important goal of this program is to understand in detail how these ionized species are produced from the gas emitted by volcanoes on Io itself.

2. Voyager and IUE both observed aurorae on Jupiter implying interesting plasma-magnetosphere interactions. What are these interactions and how do the resultant high energy particles influence the upper atmosphere chemistry of the planet? Spatial resolution of, say, 1 arcsec along the slit would be helpful for this study, as would a spectral resolution of roughly 2000 in the 100-1200 Å range to identify the highly ionized species.

3. A major goal of solar system research is to determine the initial chemical composition of the planets and their satellites. In the atmosphere of Titan, for example, the noble gases argon and neon should be primeval and their abundances can be determined from column densities of their resonance lines at 1048 Å and 1066 Å (A I) and 736 Å (Ne I). The nitrogen in Titan's atmosphere was originally locked up in NH₃, but photodissociation and the subsequent loss of hydrogen from the atmosphere means that nitrogen is now mainly in the form of N I and N II. These ions have many lines in the 912-1200 Å spectral range.

4. There are other important questions that FUSE can address, such as the atmospheric composition of Venus and the composition of Saturn ring particles and comets. These studies require that the spacecraft follow moving targets, point reasonably close to the Sun, and monitor targets for long periods of time to study seasonal changes and changes induced by different conditions in the solar wind.

4.7 Conclusions

This summary of some important scientific questions highlights the great value of a satellite capable of high throughput high resolution spectroscopy in the 912-1216 Å spectral range would be for all of astronomy. Such a mission has sufficient justification to fly if only this spectral range were available. We have mentioned some of the additional scientific benefits that would accrue from some overlap with the Space Telescope spectral range. Simultaneous observations of the Na V λλ1238, 1242 and C IV λλ1548, 1551 multiplets, for example, would clearly be desirable if they do not affect the cost substantially. However, many new and incredibly valuable scientific goals could be achieved by extending the spectral range down to 100 Å. We believe that this extended spectral range would make FUSE a far more powerful and, indeed, a unique scientific instrument.

5. INSTRUMENTAL CONSIDERATIONS AND A PROPOSED DESIGN FOR FUSE

We now discuss the various considerations that have led us inexorably to propose a new type of telescope-spectrograph combination to accomplish the objectives of FUSE.

5.1 Reflectivity of Optical Surfaces

The primary spectral range of FUSE is 912-1216 Å as defined by the previously described scientific objectives and the clear mandate of the Field Committee report (Ref. 17). The IUE and Space Telescope optical surfaces are aluminum overcoated with MgF₂. This material is commonly used because of its good reflectivity at λ > 1200 Å and its long-term stability, but as shown in Fig. 2, its reflectivity at normal incidence decreases precipitously at about 1175 Å to less than 20%. One possible solution to this low throughput problem, which has been adopted in the Magellan instrument design, is to build an instrument with only one reflecting surface to operate in the 500-1550 Å spectral region. Such an instrument is feasible (Ref. 18), but it has essentially no throughput at λ < 600 Å, and the single reflective surface design imposes other compromises in the λ > 912 Å spectral region, the most important of which is limited simultaneous spectral coverage at high spectral resolution.

![Reflectivity Graph](image)

Fig. 2. Reflectivity at normal incidence for optical surfaces coated with clean MgF₂, LiF, and a typical heavy metal, rhenium.

An alternative material is LiF, which was used to overcoat the Copernicus optical surfaces, but the normal reflectivity of LiF decreases precipitously at about 1025 Å (see Fig. 2) and is thus unsuitable for the whole 912-1216 Å spectral range. In particular, the C III (977 Å), O VI (1032, 1038 Å), and the higher Lyman lines (1025, 972 Å) would be in the region of poor sensitivity especially if there were more than one reflecting surface. Heavy metals such as rhenium have low reflectivity at all wavelengths, although they are better than LiF at 300-1025 Å.
The second alternative is to go to optical systems in which all reflections are at grazing incidence. X-ray astronomers have successfully used grazing incidence optics for many years, employing designs with graze angles of $\approx 1^\circ$ in HEOG-2 to obtain reasonably high throughput at wavelengths as short as 3 Å (4 keV). As shown in Fig. 3, the EUV places much less severe demands on the allowable graze angles. Angles as large as 10-15° permit high reflectivity even at 100 Å. This is important since large graze angles permit more compact designs that nearly fill the available aperture. Thus grazing incidence, in principle, can permit high throughput optical systems for the full 912-1216 Å spectral range and at no additional cost or complexity for the 100-912 Å and the $\lambda > 1216$ Å spectral regions as well. The important question is whether efficient high resolution spectrographs are possible and whether they can be built at reasonable cost.

![Fig. 3. Reflectivity of gold as a function of illumination angle, where 90 degrees is normal incidence.](image)

5.2 Possible Optical Designs

McClintock and Cash (Ref. 19) have investigated various telescope-spectrograph designs for graze angles of roughly $10^\circ$. They proposed that the best telescope design is the Wolter Type II system for which throughputs of 60-65% are feasible with compact length/diameter ratios of 3:1. They pointed out that an important component for high throughput spectrograph design is the placement of diffraction gratings in the conical diffraction mount (Ref. 20) illustrated in Fig. 4. The advantage of this configuration over the normal mounting of gratings is that the angles of incidence and reflection are equal, and thus both can be at nearly grazing incidence. Efficiencies of greater than 3% have been measured for even old gratings at graze angles of $10^\circ$ and $1048$ Å.

![Fig. 4. The geometry of conical diffraction. Note that the diffraction grating is illuminated along the groove direction.](image)

cross disperser grating. The conventional echelle spectrograph design, successfully used by IUE, is shown in Fig. 5. Until recently no grazing incidence analogs had been proposed, but McClintock and Cash (Ref. 19) showed that one design is feasible. Their design (see Fig. 5) consists of six optical surfaces rather than three in the conventional design, but is analogous in other ways. It consists of a two-element grazing collimator, flat echelle and cross-dispersers, and a two-element grazing camera mirror system.

This system meets the objectives stated above, but the placement of an echelle grating in the conical projection mount does have the limitation that since the angle $\gamma$ is small (because of the need for grazing incidence) resolutions are limited to only $\lambda/\Delta \lambda \approx 2-3 \times 10^5$, in order to achieve a resolution of $\lambda/\Delta \lambda = 1 \times 10^5$, the echelle must be illuminated at near normal incidence. This is feasible in a hybrid design (see Fig. 6), in which the echelle is the only normal incidence optical element.

At wavelengths longer than 912 Å the problem of spectral contamination from higher orders is negligible due to the high interstellar opacity and the relative faintness of sources in the EUV. For observations between 180 and 912 Å, however, higher order contamination is potentially a major problem. An array of ultrathin filters on a wheel at the entrance to the spectrograph could be built to reject high orders and scattered long wavelength light. These filters would reduce the throughput of the instrument, and thus would only be used in those instances where light contamination proves to be a problem.
5.3 Effective Areas and Simulated Count Rates

We now estimate total system throughputs assuming a telescope diameter of 1 m and throughput of 60% (corresponding to 4710 cm² effective area), the reflectivity of gold at 10⁴ graze angle (see Fig. 3), realistic efficiencies of gratings at 10⁴ graze angles, and a detector quantum efficiency of 35%. We consider three configurations: a low dispersion mode (Δλ/Δλ = 2000) consisting of the grazing incidence spectograph with the echelle replaced by a flat mirror, a medium dispersion mode (Δλ/Δλ = 2×10⁸) with the grazing incidence spectograph, and a high dispersion mode (Δλ/Δλ = 1×10⁵) using the hybrid spectograph (echelle grating at normal incidence).

As an example of what system throughputs might be achieved we show in Figs. 7, 8 system-effective areas for the low dispersion mode at 800-1200 Å and at 100-160 Å. The corresponding counts per spectral resolution element are illustrated in Figs. 7, 8 assuming 10⁴ seconds observing time for the active Sun at a distance of 25 pc (m_V = 7), an unreddened 09 star at a distance of 400 kpc (m_V = 18), and an unreddened m_V = 17 or 15 quasar. Each of these observations has usable signal-to-noise, assuming only photon counting statistics.

We show in Fig. 9 estimated system effective areas for one echelle order centered on the O VI lines in the middle resolution mode. The corresponding simulated count rates for the active Sun at 25 pc, an unreddened m_V = 17 09 star, and an unreddened m_V = 16 quasar are shown in Fig. 9. The signal-to-noise is entirely adequate for the first two sources, and even for the quasar the flux and line width can be measured reliably.

5.4 A Candidate Detector for FUSE

The FUSE design requires an efficient, photon-counting, two-dimensional detector system to accommodate the full echelle format. Detector dimensions of at least 1000 × 1000 with small pixel sizes (roughly 25 × 25 µm) are needed. The Working Group believes that the best available detectors at this time are the Multi-Anode Microchannel Array (MANA) detectors now being built by J. G. Timothy and collaborators (Ref. 21). These detectors consist of microchannel plates with photocathode materials deposited directly on the plates, and two-dimensional position-sensitive readouts. Formats as large as 256 × 1024 have been tested and will fly this summer on the BUSS experiment. Formats of 1024 × 1024 with 25 µm spacing are scheduled to be built within one year, and larger formats may be feasible.

MANA detectors have a number of characteristics that make them ideally suited for the FUSE mission. They operate in a photon counting mode, and have been demonstrated to be geometrically and photometrically stable for long periods of time. They have large fractional open areas (up to 85%), and can be fabricated on curved surfaces to accommodate curved focal planes. Present designs permit count rates up to 700 counts per second per (25 × 25) µm pixel without loss of counts. Finally the areas can be partially read out to permit realtime observations of rapidly variable phenomena when telemetry is limited.
Fig. 8 (above). Effective area (top panel) of the grazing incidence telescope-spectrograph-detector system at low resolution ($\lambda/\Delta \lambda = 2000$) for the range 100-160 Å. Estimated counts in $10^6$ seconds observing per pixel are given for a star like the active Sun at 25 pc (middle panel) and for an unreddened $m_V = 15$ quasar (bottom panel).

Fig. 7 (left). Effective area (top panel) of the grazing incidence telescope-spectrograph-detector system at low resolution ($\lambda/\Delta \lambda = 2000$) for the range 800-1200 Å. Estimated counts in $10^6$ seconds observing per pixel (2 pixels per spectral element) are given for a star like the active Sun at 25 pc (second panel), for an unreddened $m_V = 18.09$ star (third panel), and for an unreddened $m_V = 17$ quasar (bottom panel).
6. DESIRABLE PERFORMANCE CHARACTERISTICS FOR FUSE

Since it is premature at this time to consider trade-offs between cost and instrumental performance, we can only list the desirable performance characteristics and the scientific objectives that drive these performance characteristics. Most of the science drivers have been discussed above, but the question of desired spectroscopic resolution must be considered here.

6.1 Desirable Spectral Resolution

Observations of H$_2$ and other lines formed in cold interstellar clouds place the most severe demands upon spectroscopic resolution. In Fig. 10 we show a spectrum of the sodium D$_2$ line for the line of sight toward ε Ori obtained at λ/Δλ = 6×10$^5$ by Hobbs (Ref. 22), together with the same spectrum degraded to resolutions of 1.2×10$^5$ and 2.2×10$^4$. Clearly a resolution of 1×10$^5$ is needed to preserve the essential details of the original spectrum and thus permit determination of column densities in the individual velocity components. Thus we need a resolution of 1×10$^5$ in the 912-1216 Å spectral range. At other wavelengths a resolution of 2×10$^5$ is adequate for line profile studies and resolutions of 2×10$^3$ and 2×10$^2$ are adequate for line flux measurements. The lowest resolution mode is necessary to study faint extragalactic sources.

6.2 A Summary of the Desirable FUSE Performance Characteristics

We list in Table 3 the desired spectral resolution, instantaneous spectral range, and field of view and angular resolution needed for long slit spectroscopy. IUE has demonstrated the desirability of complete wavelength coverage over a large spectral range. This is easily achieved at low resolution. The use of two-dimensional detectors and an echelle format allows broad spectral coverage at high spectral resolution, so that the stringent requirements of Table 3 can actually be achieved at moderate cost. The different wavelength ranges are easily achieved by a drum that rotates different gratings into the spectrograph beam. A single 1024 x 1024 detector could be used for all these wavelength ranges.

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**Fig. 9 (left).** Effective area (top panel) of the grazing incidence telescope–spectrograph-detector system at middle resolution (λ/Δλ = 2×10$^4$) for one order centered on the O VI λλ1032,1038 lines. Estimated counts in 10$^6$ seconds observing per pixel are given for a star like the active Sun at 25 pc (second panel), for an unreddened $m_V = 17$ 09 star (third panel), and for an unreddened $m_V = 16$ quasar (bottom panel).
Fig. 10. A spectrum of the sodium D2 line for the line of sight toward ε Ori obtained at
\( \lambda / \Delta \lambda = 6 \times 10^{15} \) by Hobbs (Ref. 22) and degraded to resolutions of 1.2 \( \times 10^{5} \) and 2.2 \( \times 10^{4} \).

Table 3.
Desirable FUSE Performance Characteristics

<table>
<thead>
<tr>
<th>Spectral Range</th>
<th>900 - 1216 Å</th>
<th>500 - 912 Å</th>
<th>100 - 500 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Resolution</td>
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<td>2-3 ( \times 10^{4} )</td>
<td>2-3 ( \times 10^{4} )</td>
</tr>
<tr>
<td>Instantaneous</td>
<td>Complete</td>
<td>Large</td>
<td>Complete</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>(many orders)</td>
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<td></td>
</tr>
<tr>
<td>Field of View</td>
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<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>1 arcsec</td>
<td>1 arcsec</td>
<td>1 arcsec</td>
</tr>
</tbody>
</table>

7. CONCLUSIONS

We wish to emphasize again the preliminary nature of the FUSE mission concept, and the consideration of poor normal reflectivity of all known materials at \( \lambda < 1025 \) Å that has driven us to grazing incidence telescope-spectrograph designs. Once we have made the decision to adopt grazing incidence optics to observe the full 912-1216 Å spectral range, then we have in principle an optical system with high throughput from 100 Å to the optical. The only limitation at longer wavelengths is the photocathode material on the detector. Since solar-blind detectors are essential for ultraviolet observations of cool stars and solar system objects, GeI is the likely photocathode material and the system will be sensitive to radiation up to about 1700 Å. Some obvious advantages of the FUSE concept are:

1. Wide spectral range (100-1700 Å) with the same instrument and optical path.

2. The ability to study many targets with low and moderate spectral resolution in the previously inaccessible 100-912 Å spectral range. This ability permits the study of a new class of problems in astrophysics.

3. A flexible instrument with the ability to change spectral resolutions and ranges by means of many gratings on a drum.

4. No source confusion because the telescope has good angular resolution.

5. Little if any problem of scattered light.

6. The ability to obtain spatially resolved spectra along the slit.

7. An instrument that is very different from its predecessors, IUE and HRS.

There are some possible negative aspects, however, that future investigations must address:

1. What is the cost?

2. Is the new optical design feasible?

3. Can this instrument be accommodated on the spacecraft and launch vehicles that will likely be available in the near future?

The FUSE Science Working Group activity is supported by NASA.
8. REFERENCES
