The extra-terrestrial vacuum-ultraviolet wavelength range

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Abstract

Electromagnetic radiation in the vacuum-ultraviolet (VUV) and extra-terrestrial range at wavelengths from 10 nm to 300 nm is absorbed in the upper atmosphere by ozone, molecular and atomic oxygen, and molecular nitrogen. Observations at wavelengths down to \( \approx 200 \) nm can be carried out from stratospheric balloons, and observations below 200 nm require space platforms operating at altitudes above 250 km. The VUV spectral region contains emission lines and continua arising from plasma at formation temperatures ranging from about \( 10^4 \) K to more than \( 10^7 \) K. This chapter describes the wide range of plasma diagnostic techniques available at VUV wavelengths, and the development of instrumentation for studies of the high-temperature solar outer atmosphere and astrophysical plasmas. Finally, the prospects for future studies are briefly discussed.

The early days

It has been known for many years that the outer atmosphere of the Sun is significantly hotter than the 5800 K temperature of the photosphere, particularly from observations of forbidden coronal lines at 637.5 nm (Fe x—red line) and 530.3 nm (Fe xiv—green line) by Lyot (1937), Grotrian (1939), and Edlén (1943). The Sun must emit strong ultraviolet (UV) radiation from these regions at wavelengths shorter than those of the visible spectrum (\( \lambda \approx 400 \) nm to \( \approx 800 \) nm). However, ground-based efforts to explore this wavelength regime have met with only limited success. This is because of the onset of very strong absorption at wavelengths below \( \approx 290 \) nm by ozone at altitudes between about 15 km and 35 km (Massey and Boyd 1960).

At shorter wavelengths below \( \approx 200 \) nm molecular oxygen in both the Herzberg dissociation continuum and the Schumann-Runge bands causes complete absorption at higher altitudes, and atomic oxygen and molecular nitrogen at wavelengths below \( \approx 90 \) nm cause absorption at altitudes above 160 km. The altitude at which
the fraction of the vacuum-ultraviolet (VUV) radiation is reduced by a factor of 1/e is shown in Figure 5.1.

Atmospheric effects

Currently there is considerable concern about the increasing depletion of the ozone layer, caused by photo-dissociation of chlorofluorocarbon compounds (CFCs), which could expose the biosphere to increasing levels of UV-A (315 nm to 380 nm) and UV-B (280 nm to 315 nm). This has led to a phase-out and ban on the production and use of CFCs by the US Environmental Protection Agency in 1994 and 1996 under extensions to the 1987 Montreal Protocol. A critical example of ozone depletion is the annual formation of an ozone “hole” over Antarctica. UV-B radiation is known to cause skin cancer, and significant increases in skin cancer and melanoma have been recorded in Chile as the direct result of the expansion of the ozone “hole” (Abarca and Casiccia 2002). UV-A radiation may also play a role in causing melanomas, although the effects are mediated by reactive oxygen species (de Gruijl 2002).

VUV radiation at wavelengths below $\approx 120$ nm is responsible for the heating of the thermosphere and the formation of the E and F regions of the ionosphere (Timothy et al 1972). However, the very strong hydrogen Ly $\alpha$ emission line at 121.6 nm coincides with a window in the $O_2$ absorption cross-section, which allows the radiation to penetrate to below 90 km, where together with VUV radiation at wavelengths longer than $\approx 180$ nm and soft X-rays, it forms the D region of the ionosphere (Nicolet and Aikin 1960).

\footnote{For details see http://www.epa.gov/ozone.}
An example of the fitting of a Jacchia model profile (Jacchia 1971, 1977) to a measured sounding rocket profile of the strong He I 58.4 nm resonance line is shown in Figure 5.2.

### Observing platforms and enabling technologies

Whereas measurements at wavelengths down to \( \approx 200 \text{ nm} \) are possible from high-altitude balloons floating at altitudes above 40 km, measurements at shorter wavelengths require the use of sounding rockets, satellites orbiting at altitudes well above 160 km, or space probes. Even at altitudes above 200 km residual absorption by the geocorona and terrestrial airglow emission can affect the measurements. The initial measurements were directed at studies of the solar VUV emission because of the relatively high irradiances. Studies of fainter astrophysical objects followed at a later date as the technology improved.

The earliest sounding rocket measurements were made in the US in the late 1940s using, first, captured German V2 rockets, and then US-developed Aerobee rockets. The data obtained with these unstabilized rocket systems were limited and special techniques were required to direct the solar VUV radiation into the spectrometers (de Jager 2001; Wilhelm 2003). Limited measurements of the solar
VUV spectrum were obtained down to \( \approx 200 \) nm. The development in the 1950s and 1960s of more powerful sub-orbital and orbital launch vehicles (Russo 2001) was the key to future progress. The development of two-axis and three-axis pointing systems, first for sounding rockets and, later, for orbiting satellites, allowed not only the exploration of the solar VUV, but also permitted the first observations of VUV emission from astrophysical objects.

The early spectra and images at VUV wavelengths were recorded using photographic emulsions. Conventional emulsions have extremely low sensitivities at VUV wavelengths because of absorption by the gelatin layer containing the silver halide grains. Special emulsions for VUV studies, where the silver halide grains were located on or very near the surface of the gelatin were developed by Schumann (1901). The early Schumann emulsions were fabricated on glass plates, which are not suitable for use in the launch environment for space vehicles, and are extremely sensitive to contamination and are destroyed by physical contact. In the years leading up to the Skylab flight in 1973, a series of special film-based Schumann emulsions and their holders were successfully developed (VanHoosier et al 1977). Since the solar VUV radiation arises in the hot outer atmosphere of the Sun and is many magnitudes fainter than the intense visible light radiation from the photosphere (cf., Figure 2.2 in Chapter 2, Wilhelm and Fröhlich 2010), the development of “solar blind” detector systems insensitive to visible light was critical to the fields of VUV solar and astrophysical studies (see Chapters 22, 25, and 26, Timothy 2010; Schühle 2010; Schühle and Hochdez 2010). Further, at wavelengths below \( \approx 116 \) nm no rugged window materials are available. Hence there is a need for reflective optical systems, and for detector systems that can operate without windows at shorter wavelengths. Finally, the reflectance of normal-incidence optical systems falls dramatically below \( \approx 50 \) nm, and the use of grazing-incidence telescopes (Brueggemann 1968) and spectrometers (Samson 1980), or synthetic multilayer interference coatings (Spiller 1974), is mandatory.

**Physical processes**

The solar VUV spectrum at wavelengths longer than about 200 nm is fundamentally similar to the solar visible light spectrum, namely, a radiation continuum with superimposed Fraunhofer absorption lines. Below about 200 nm the spectrum is densely populated with strong emission lines and continua formed at temperatures from about \( 4 \times 10^3 \) K to greater than \( 10^7 \) K. The corresponding energetic photons are responsible for critical processes in the atmosphere of the Earth, such as photodissociation of key atmospheric molecules, the formation of the different layers of the ionosphere, and the heating of the thermosphere (Timothy et al 1972). In addition, the very wide range of excitation and ionization temperatures makes this spectral region ideal for studies of the hot outer regions of the atmospheres of the Sun and other stars, and for the investigation of other high-temperature and dynamic phenomena in the Universe.

In order to use the VUV emission lines for plasma diagnostics, the processes leading to the formation of the emission lines and continua must be fully understood. Wilhelm et al (2004) have presented a detailed review (with many referenc-
ces) of the processes of spectral line formation and plasma diagnostic techniques, specifically for studies of the solar chromosphere, transition region, and corona. We review briefly here some of the key issues.

Spectral line formation

Some of the radiation in the VUV range is emitted by atoms, notably by neutral hydrogen and helium, but many of the VUV spectral lines are generated by ions of heavier elements. One of the key processes for producing the ions is electron impact ionization:

\[ X^+Z + e^- \rightarrow X^{+(Z+1)} + 2e^- , \]  

(5.1)

where \( X^+Z \) is a \( Z \)-fold charged ion of element \( X \) and \( e^- \) on the left-hand side is an electron with sufficient kinetic energy, \( W \), to provide the required ionization energy, \( W_0 \). This process has to compete with recombination to lower charge states and further ionization to higher charge states.

VUV spectroscopic plasma diagnostics

The wide range of ionization energies at VUV wavelengths renders this radiation extremely useful for a number of plasma diagnostic techniques. These include:

Emission measures

Many plasmas in the Universe are optically thin, and therefore the radiation emitted is seen by a detector as integrated along the line of sight (LOS) of length \( z_0 \). In general, excited atoms and ions spontaneously emit photons as the main depopulation process. The probability for a radiative transition from state \( j \) to state \( i \) is given by the Einstein coefficient, \( A_{ji} \). The radiant power density\(^2\) in a spectral line at \( \lambda_{ji} \) is

\[ \varphi(\lambda_{ji}) = \Delta \varepsilon_{ij} A_{ji} n_j , \]  

(5.2)

where \( \Delta \varepsilon_{ij} \) is the energy difference between the states \( i \) and \( j \) and \( n_j \) is the number density of the radiating species in state \( j \). The quantity \( \varphi(\lambda_{ji}) \) can be obtained from the spectral radiant power density, \( \varphi_\lambda \), by integrating over the line profile and deduction of the background:

\[ \varphi(\lambda_{ji}) = \frac{\lambda_{ji} + \delta \lambda/2}{\lambda_{ji} - \delta \lambda/2} \int (\varphi_\lambda - b_\lambda) \, d\lambda . \]  

(5.3)

The background, \( b_\lambda \), can be determined from the shape of the spectrum near the spectral line.

An emission measure (EM) (Pottasch 1963) can then be defined as

\[ \int_{z_0} n_e^2 \, dz = \frac{\langle \varphi(\lambda_{jj}) \rangle z_0}{\gamma \Delta \varepsilon_{jj} G(T_e) n_X n_H} n_e n_H = \frac{4\pi L(\lambda_{jj})}{\gamma \Delta \varepsilon_{jj} G(T_e) n_X n_H} n_e n_H , \]  

(5.4)

\(^2\)Often called in the literature “emissivity”, which is, however, the ratio of the emission of a surface to the corresponding black-body radiation.
with \( n_e \) the electron density, \( \langle \varphi(\lambda_{jg}) \rangle \) the average power density along the LOS, and \( L(\lambda_{jg}) = \langle \varphi(\lambda_{jg}) \rangle z_0/(4\pi) \) the observed radiance of the emission line at \( \lambda_{jg} \). The element abundance of element X with respect to hydrogen is \( n_X/n_H \) and the number density of hydrogen relative to the electron density is \( n_H/n_e \) (cf., Wilhelm et al 2004). The factor \( \gamma \) can be obtained from atomic physics calculations. The contribution function, \( G(T_e) \), is defined by (see, e.g., Mariska 1992):

\[
G(T_e) = \frac{n_g}{n_X} \frac{1}{\sqrt{T_e}} \exp \left( -\frac{\Delta \varepsilon_{gj}}{k_B T_e} \right),
\]

where \( k_B \) is the Boltzmann constant and \( n_g/n_X \) the ionic fraction (Mazzotta et al 1998). The contribution function has its maximum at the formation temperature of the line. As an example we show in Figure 5.3a the ionic fractions of the element magnesium as a function of the electron temperature, \( T_e \), taken from Mazzotta et al (1998), and in Figure 5.3b the corresponding contribution functions calculated with the help of Equation 5.5. The assumptions made above include that the plasma is iso-thermal along the LOS at a certain temperature, \( T_e \). If there are temperature gradients along the LOS, a differential emission measure (DEM), \( \Phi(T_e) \), must be used (Athay 1966). The integration is then performed over a certain temperature interval, \( T \pm \Delta T/2 \), in which the spectral line is formed:

\[
\int_{z_0} G(T_e) n_e^2 \, dz = \int_{\Delta T} G(T_e) \Phi(T_e) \, dT_e,
\]
with the DEM defined by

$$
\Phi(T_e) = n_e^2 \frac{dz}{dT_e} .
$$

(5.7)

If the plasma is optically thick, direct information can only be obtained about the “surface” by analyzing the spectral radiance. In intermediate cases, radiative transfer processes within the plasma have to be considered as well.

**Density-sensitive line ratios**

Collisionally-excited states may be depopulated by non-radiative processes, in particular, if they are metastable. The radiant power density is thus reduced for lines from such states as a function of $n_e$. The ratio

$$
R_{12} = \frac{\varphi(\lambda_1)}{\varphi(\lambda_2)}
$$

(5.8)
of an allowed emission line at $\lambda_1$ and a metastable line at $\lambda_2$ is consequently changing with $n_e$, and can be calculated from atomic physics principles. From Equation 5.4, we may conclude that this can be accomplished by measuring the ratio of the line radiances

$$
R_{12} = \frac{L(\lambda_1)}{L(\lambda_2)} .
$$

(5.9)

This method is especially useful if both lines are emitted by particles of the same species and ionization stage, because abundance and ionization variations will have no effect (cf., e.g., Doschek et al 1997).

The electron density so determined can, under certain assumptions, be compared with the mean density obtained from the emission measure analysis and provide information on the so-called “filling factor” (cf., Dere et al 1987).

**Temperature-sensitive line ratios**

If two excited states, $j_1$ and $j_2$, from which emission lines originate, have very different energy levels, their relative collisional excitation becomes a function of the electron temperature, $T_e$, and the ratio can again be obtained from atomic physics calculations. A comparison with the measured ratio of the line radiances then provides information on the electron temperature (cf., e.g., David et al 1998).

**Element abundances**

Two lines at $\lambda_1$ and $\lambda_2$ from different species, but with very similar contribution functions, stemming from the same location, and thus generated at the same electron density, emit radiant power densities, $\varphi(\lambda_1)$ and $\varphi(\lambda_2)$, or, from Equation 5.4, the corresponding line radiances (adjusted for any variations of $\Delta \varepsilon_{ij}$ and $\gamma$). Their ratio can be used to obtain the element abundance ratio $n_X/n_H$. Variations of abundances are caused both in the corona and in the solar wind, in particular, by the first-ionization potential (FIP) effect (Feldman and Laming 2000).
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Figure 5.4: Doppler shifts in transition region lines caused by upward and downward flows in an explosive event with speeds up to 100 km s$^{-1}$ (observation from the SUMER instrument on SOHO, described in Table 5.1).

Ion motions and temperatures

The non-relativistic Doppler formula

\[ v = c_0 \frac{\lambda - \lambda_0}{\lambda_0} = c_0 \frac{\Delta \lambda}{\lambda_0}, \]  

(5.10)

where \(c_0\) is the speed of electromagnetic waves in vacuo and \(\lambda_0\) is the rest wavelength of an emission line, is adequate for most of the speeds encountered in solar and stellar atmospheres. Equation 5.10 allows a conversion of measured line shifts or spectral profiles\(^3\) into plasma motions along the LOS, either as average bulk velocity, or as the corresponding component of unresolved small-scale turbulence.

With \(m_i\) the mass of the ion and \(\Delta \lambda_D\) the Doppler width\(^4\), thermal and non-thermal contributions, e.g., turbulence, affect the profile according to

\[ \Delta \lambda_D = \frac{\lambda_0}{c_0} \sqrt{\frac{2 k T_i}{m_i}} + \xi^2, \]  

(5.12)

where \(T_i\) is the ion temperature and \(\xi\) the most probable non-thermal LOS velocity (see, e.g., Mariska 1992). Examples of emission lines affected by Doppler shift are shown in Figure 5.4.

Atomic databases

As the quality of the observations improved, the development of atomic databases for spectroscopic diagnostics in the VUV began (see, e.g., Mason and Monsignori Fossi 1994). A highly detailed computer program called CHIANTI, using atomic data and transition rates, has been developed to allow the computation of synthetic spectra and the application of plasma diagnostic techniques. The first version was

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\(^3\)Any instrumental line broadening is assumed to have been taken out before.

\(^4\)For a Gaussian profile of an emission line at \(\lambda_0\), the Doppler width, \(\Delta \lambda_D\), is related to the standard deviation, \(\sigma\), and the full-width at half maximum (FWHM), \(\Delta \lambda_{\text{FWHM}}\), through the equation:

\[ \Delta \lambda_D = \sigma \sqrt{2} = \Delta \lambda_{\text{FWHM}}/(2\sqrt{\ln 2}) . \]  

(5.11)
## Table 5.1: Key solar physics orbital and deep space missions from 1980 through 2008.

<table>
<thead>
<tr>
<th>Year</th>
<th>Mission</th>
<th>Instrument Parameters</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Polarisometer (UVSP) ∆λ : 2 pm</td>
<td>Brueckner et al (1986)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Resolution Telescope and Spectrograph (HRTS) 120 nm . . . 170 nm</td>
<td>Lang et al (1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coronal Helium Abundance Experiment (CHASE) 17 nm . . . 133.6 nm</td>
<td>VanHoosier et al (1988)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar Ultraviolet Irradiance Monitor (SUIM) ∆λ : 0.15 nm and 0.5 nm</td>
<td>Brueckner et al (1993)</td>
</tr>
<tr>
<td>1985</td>
<td>Spacelab 2</td>
<td>High Resolution Telescope Stigmatic spectra 121.6 nm</td>
<td>Lean et al (1992)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and Spectrograph (HRTS) 120 nm . . . 400 nm</td>
<td>Brueckner et al (1995)</td>
</tr>
<tr>
<td>1993</td>
<td>Spartan 201</td>
<td>Ultraviolet Coronal Spectrograph (UCS) 103.2 nm, 103.7 nm</td>
<td>Kohl et al (1994)</td>
</tr>
<tr>
<td>1995</td>
<td>SOHO</td>
<td>Coronal Diagnostic Spectrometer (CDS) 121.6 nm</td>
<td>Harrison et al (1995)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extreme-ultraviolet Imaging Telescope (EIT) 17.1 nm . . . 30.4 nm</td>
<td>Delaboudinière et al (1995)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar EUV Monitor (SEM) 30.4 nm, 17 nm . . . 70 nm</td>
<td>Hovestadt et al (1995)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar Ultraviolet Coronagraph 103.2 nm, 103.7 nm</td>
<td>Kohl et al (1995)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectrometer (UVCS) 121.6 nm</td>
<td>Hand et al (1999)</td>
</tr>
<tr>
<td>2001</td>
<td>TIMED</td>
<td>Solar EUV Experiment (SEE) 0.1 nm . . . 195 nm</td>
<td>Woods et al (1998)</td>
</tr>
</tbody>
</table>

published in 1996 (Dere et al 1997), and an updated version was published in 2006 (Landi et al 2006). CHIANTI has not only been used widely for solar studies, but also for studies of coronae of cool stars, a wide range of other stars, and non-stellar objects such as supernova remnants. A comparison of an observed active region spectrum and a synthetic spectrum produced by use of the CHIANTI code is shown in Figure 5.5 (Mason et al 1997).

### Solar physics observations

The Sun is the only star where detailed VUV observations of the surface structure have been possible to date. A strong programme of solar observations at VUV wavelengths has continued from 1946 to this day (de Jager 2001; Wilhelm et al 2007). Fueled by the awareness of the unique properties of the outer solar atmosphere as an astrophysical laboratory and by increasing evidence for solar effects on the terrestrial atmosphere and possible effects on the terrestrial climate, a clear bifurcation in the types of observation has evolved: first, spectral-imaging studies of the solar atmosphere with increasing spatial and spectral resolutions, and, second, measurements of the solar VUV irradiance with increasing radiometric accuracy. Wilhelm et al (2004) have presented a list of some of the important solar observa-
There were a number of notable advances during this period. Hinteregger et al. (1964) and Hall et al. (1965) recorded the first measurements of the VUV spectrum below \( \approx 30 \) nm, including the discovery of the strong emission lines of Fe\text{IX} through Fe\text{XIII} at wavelengths between 17 nm and 22 nm (see Figure 5.5). The sounding rocket spectrometers employed grazing-incidence optics and open-structure photo-electric detector systems. Reeves and Parkinson (1970) produced the first detailed atlas of spectroheliograms at VUV wavelengths between 30 nm and 140 nm using the Harvard College Observatory (HCO) instrument on the \textit{OSO} 4 mission. The spectroheliometer employed a normal-incidence platinum-coated telescope mirror and a gold-coated normal-incidence diffraction grating. The detector was a solar-blind open-structure photon-counting magnetic electron multiplier (see Chapter 22). Also with the help of \textit{OSO} 4 Timothy and Timothy (1969) recorded the first long-term irradiance variations in the strong He\text{II} Ly\(\alpha\) line at 30.3 nm.

The most comprehensive solar-physics mission of the 1970s was the \textit{Skylab} Apollo Telescope Mount (ATM). A detailed overview of this mission has been given by Tousey (1977), see also Bartoe and Brueckner (1975). This mission, coming at the end of the Apollo programme, was unique in a number of ways. First, the solar instruments were the largest ever flown. Second, it was the first mission where on-board astronauts controlled the different solar instruments using both...
photographic and photoelectric detector systems in a series of coordinated observing programmes. Third, it was one of the first missions to use sounding rocket under-flights to successfully recalibrate some of the instruments during the mission (see, e.g., Reeves et al 1977).

The many results from ATM included the first direct observations of the chromospheric network (Reeves et al 1974), the expanded transition region over polar coronal holes (Huber et al 1974), high angular-resolution\(^5\) (≈ 2''\(^5\)) whole disk spectroheliograms (Tousey et al 1977), measurements of VUV emission line profiles (Bartoe et al 1977), and the identification of coronal holes as the source of the high-speed streams in the solar wind (Krieger et al 1973).

The results of all of these early studies led to a general understanding of solar atmospheric conditions. Mean height profiles of the temperature and hydrogen density of the solar atmosphere in a quiet region are shown in Figure 5.6. Nevertheless, the details of the mechanism(s) for heating the coronae of the Sun and other stars remain an active field of research to this day.

It was also learned that the solar atmosphere is both highly structured and highly dynamic. The general structure of the magnetic field configuration in a quiet region of the transition region and lower corona is shown in Figure 5.7. Studies have been presented both of the heating of the solar corona (Kuperus 1969), and of the structure of the transition region (Mariska 1986). However, what became obvious from these early results was that the solar atmosphere is extremely dynamic, not only in small and large scale magnetic reconnection events such as bright points.

\(^5\)An angular resolution element of 1'' at 1 ua corresponds to spatial scale of ≈ 725 km on the solar disk.
and solar flares, but also in the “quiet” atmosphere. Observations on timescales of seconds or less are thus required to fully address the physics.

Further, the basic phenomena controlling the outer atmosphere and heating the solar corona take place at the smallest spatial scales (< 100 km), requiring observations from 1 au with angular resolutions of 0.1″ or smaller.

During the late 1970s, there was a dearth of orbiting solar VUV missions. However, during this period there was a series of sub-orbital sounding rocket flights, particularly those measuring the solar irradiance (see, e.g., Mount et al 1980). A key development was the invention of the Tandem–Wadsworth spectrograph by Bartoe and Brueckner (1975). This led to a series of flights from 1975 through 1992, resulting in more than 100 publications (see, for example, Dere et al 1987). Also, during this period Kohl et al (1978) produced an atlas of the solar spectrum in high resolution at wavelengths between 225.2 nm and 319.6 nm. A number of solar irradiance instruments were also flown on sounding rockets (Mount et al 1980).

This period ended in 1980 with the launch of the SMM. The key solar VUV missions from 1980 to 2008 are listed in Table 5.1.

All of the early VUV solar-physics instruments were on platforms in low Earth orbit. This led to about 60 min of solar observations, followed by 30 min in eclipse behind the Earth. The maxim in those early days was that all interesting solar phenomena occurred while the spacecraft was occulted by the Earth!

This all changed dramatically in 1995 when the ESA/NASA SOHO spacecraft was placed in a halo orbit around the L1 Lagrange point, where the solar and terrestrial gravitational fields were in balance with the centrifugal force. This allowed SOHO to observe the Sun continuously, and also monitor the solar wind upstream of the Earth’s magnetosphere. The data from SOHO were spectacular and obser-
vations continue to this day. Early results can be found in the book “The First Results from SOHO” (Fleck and Svestka 1997).

In 1998, TRACE was launched into a Sun-synchronous polar orbit (Handy et al 1999). TRACE employed a single Cassegrain telescope with multilayer-coated optics and a lumogen-coated charge-coupled device (CCD) detector to obtain an angular resolution of 1" (0.5" pixel size) at selected VUV wavelengths. The TRACE image quality is superb. The mission obtained its last science image in June 2010.

The TIMED mission was launched in December 2001 and has been obtaining solar VUV irradiance data from ≈ 0.1 nm to ≈ 195 nm since early in 2002 with the Solar EUV Experiment (SEE) (Woods et al 1998).

In September 2006 the Japanese Solar-B mission, renamed Hinode (“Sunrise”), was launched into a Sun-synchronous Earth orbit at an altitude of 680 km. The primary instrument is a 0.5 m diameter visible-light telescope, the largest solar optical instrument yet operating in space. Complementing the primary instrument is the EUV Imaging Spectrometer (EIS) covering the wavelength ranges 17 nm to 21 nm, and 25 nm to 29 nm, with an angular resolution of 1" (Culhane et al 2007).

Finally, a deep space mission, launched on October 2006, is STEREO, consisting of two identical spacecraft, one flying forward of the Earth, and the second flying behind the Earth. At separation angles between about 10° and about 15°, the two spacecraft produced high quality stereoscopic images of the solar atmosphere. As the separation angles increased, the spacecraft were able to observe progressively more of the solar atmosphere not visible from Earth, thereby giving advance warning of the development of active regions. Finally, at angles near 90° with respect to the Earth they can directly view coronal mass ejections leaving the Sun and headed towards Earth. VUV observations at wavelengths of 17.1 nm, 19.5 nm, 28.4 nm, and 30.4 nm are being carried out with the Extreme Ultraviolet Imager (EUVI), which has a field of view (FOV) out to 1.7 R⊙ (Wülser et al 2004).

Astrophysical observations

VUV astrophysics studies from space developed at a much slower rate than solar observations, primarily because of the much lower irradiance levels and the need for critical stabilization of the observing platform. Savage (2001) has given an excellent review of the technological challenges and vicissitudes of the early observing programmes. The astrophysics VUV missions from 1966 to 2008 are listed in Table 5.2. Morton and Spitzer (1966) made the first spectral observations from three-axis stabilized sounding rockets, using a VUV spectrometer with its own separate fine stabilization system. The recording medium was photographic emulsion, and the early observations concentrated on bright hot stars (see, e.g., Morton 1967).

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6Daily images can be seen at http://sohowww.nascom.nasa.gov.
7Full information and results are available at http://trace.lmsal.com. (TRACE and many other space programmes have an open data policy.)
8Information on the TIMED mission can be found at http://timed.jhuapl.edu.
9Details can be found at http://solarb.msfc.nasa.gov.
Table 5.2: Key sub-orbital and orbital astrophysics missions from 1966 to 2008.

<table>
<thead>
<tr>
<th>Year</th>
<th>Mission</th>
<th>Instrument</th>
<th>Parameters</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>1966</td>
<td>Three-axis stabilized sounding rockets</td>
<td>Spectrometer</td>
<td>126 nm . . . 172 nm</td>
<td>Morton and Spitzer (1966)</td>
</tr>
<tr>
<td>1972</td>
<td>TD 1-A Spacecraft</td>
<td>UV sky survey telescope</td>
<td>∆λ ≈ 0.1 nm</td>
<td>Boksenberg et al (1973)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stellar Ultraviolet Spectrometer</td>
<td>Three bands of 10 nm at 211 nm, 254.5 nm, 282.5 nm, ∆λ : 0.17 nm</td>
<td>de Jager et al (1974)</td>
</tr>
<tr>
<td>1972</td>
<td>OAO 3</td>
<td>Telescope and Spectrometer</td>
<td>95 nm . . . 145 nm, ∆λ : 5 pm, 165 nm . . . 300 nm, 2.5 pm</td>
<td>Rogerson et al (1973)</td>
</tr>
<tr>
<td>1976</td>
<td>BUSS (upgraded)</td>
<td>Telescope, echelle spectrometer</td>
<td>∆λ : 10 pm</td>
<td>Hoekstra et al (1978)</td>
</tr>
<tr>
<td>1978</td>
<td>IUE</td>
<td>Telescope, echelle spectrometers</td>
<td>115 nm . . . 195 nm, ∆λ : 15 pm, 190 nm . . . 320 nm</td>
<td>Boggess et al (1978a)</td>
</tr>
<tr>
<td>1990</td>
<td>HST</td>
<td>Goddard High-Resolution Spectrograph (GHRS)</td>
<td>λ/∆λ : 2 × 10^3 . . . 2 × 10^5</td>
<td>Brandt et al (1994)</td>
</tr>
<tr>
<td>1993</td>
<td>First HST Servicing Mission (HSM 1)</td>
<td>Corrective optics package (COSTAR) installed Wide Field Planetary Camera</td>
<td>0.12 pm . . . 1.0 pm</td>
<td>Hartig et al (1993)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WFPC 1 replaced by WFPC 2 GHR S performance significantly improved</td>
<td></td>
<td>Robinson et al (1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Faint Object camera (FOC) performance significantly improved</td>
<td></td>
<td>Jedrzejewski et al (1994)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectrograph (STIS)</td>
<td>λ/∆λ : upto 1 × 10^5</td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>EUVE</td>
<td>Grazing Incidence Telescopes and Spectrometers</td>
<td>6 nm . . . 75 nm</td>
<td>Sirk et al (1997)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and Spectrometers</td>
<td></td>
<td>Borucki (1997)</td>
</tr>
<tr>
<td>1999</td>
<td>FUSE</td>
<td>Normal incidence telescopes and spectrometers</td>
<td>λ/∆λ : 2 × 10^8 . . . 2.5 × 10^4</td>
<td>Sainov et al (2000)</td>
</tr>
</tbody>
</table>

It soon became apparent that the short observing time (≈ 300 s) available from sounding rockets was a severe limiting factor. The development of orbiting satellites and high-altitude balloons for astrophysical observations then began in the US and in Europe. In the US the OAO series of spacecraft (Rogerson 1963) began with the successful launch of OAO 2 (the attitude control system of OAO 1 having failed after achieving orbit) in December 1968. OAO 2 contained instruments from Wisconsin and the Smithsonian Astrophysical Observatory (SAO) (Code 1969). The Wisconsin instrument included two scanning spectrometers as well as photometers (Code et al 1970), while the SAO instrument was equipped for a VUV sky survey.

The major advance came with the launch of OAO 3 in August 1972, which was renamed Copernicus. The Princeton instrument employed an 80 cm diameter Cassegrain telescope with a scanning VUV spectrometer. The wavelength range from 165 nm to 300 nm was covered with a resolution of 2.5 pm. Open-structure photomultiplier tubes with opaque KBr photocathodes were also used for the first time allowing the wavelength range from 95 nm to 145 nm to be covered with a resolution of 5 pm (see Rogerson et al 1973).
The European Space Research Organization (ESRO) launched the TD-1A satellite in March 1972. TD-1A contained a UV sky survey telescope covering the wavelength range from 135 nm to 255 nm (Boksenberg et al 1973), and a stellar UV spectrometer covering wavelength bands around 211 nm, 254.5 nm, and 282.5 nm (de Jager et al 1974).

The Balloon-borne Ultraviolet Stellar Spectrograph (BUSS) evolved from earlier work in the US and the UK, and was a joint development by the US and The Netherlands. BUSS was designed to cover the wavelength range from 200 nm to 340 nm using an echelle spectrograph with a wavelength resolution of 10 pm (Hoekstra et al 1978). The upgraded instrument was first flown in 1975, and BUSS flights continued into the 1980s when the development of the HST rendered it obsolete.

In March 1978, IUE was launched into a geosynchronous orbit. IUE was a joint development by NASA, the UK Science Research Council (SRC), and the European Space Agency (ESA). The instrument employed a 45 cm diameter Ritchey–Chrétien telescope and two echelle spectrometers. The detectors were UV to visible light image tube convertors coupled to SEC Vidicon image tubes. The wavelength range from 115 nm to 195 nm was covered with a wavelength resolution of 13 pm, and the range from 190 nm to 320 nm was covered with a resolution of 20 pm (Boggess et al 1978a). The in-flight performance has been described by Boggess et al (1978b). Although suffering a number of attitude control system failures, IUE continued operating until September 1996, producing over 104 000 UV spectra.\footnote{Full details of the mission can be found at http://archive.stsci.edu/iue.}

The launch of HST in April 1990 marked a seminal moment in optical and VUV astrophysics. Not only does HST employ a 2.4 m aperture Ritchey–Chrétien telescope, it can accommodate one radial and four axial science instruments and is configured for on-orbit servicing and instrument replacement by astronauts (see Edelman 1990). Further, the telescope optics are coated with Al protected by a thin MgF$_2$ overcoat for good UV reflectances, and the pointing accuracy is better than 0.01′′. However, in addition to suffering from the vagaries of the Space Shuttle (STS) programme, HST has not been without its own problems. The most serious of these was that, shortly after starting science observations, it was discovered that the primary mirror (although its surface was excellently polished) had nevertheless an incorrect shape leading to spherical aberration in the image.

Included in the primary instrument package were the Goddard High Resolution Spectrograph (GHRS) (Brandt et al 1994), and the Faint Object Camera (FOC) (Greenfield et al 1991). GHRS covered the spectral range from 115 nm to 320 nm with spectral resolutions ranging from $2 \times 10^3$ to $1 \times 10^5$. For the first time GHRS used multi-element detectors to improve the observing efficiency, namely two $1 \times 512$ pixel pulse-counting Digicon arrays (Ebbets and Garner 1986). The FOC employed an electron-bombed silicon (EBS) television tube and several VUV filters between 123 nm and 215 nm.

The solutions to the spherical aberration problem were to replace the radial instrument, the Wide Field and Planetary Camera (WFPC 1), with WFPC 2 which had a corrective optical system installed, and to replace the High Speed Photometer with the Corrective Optics Space Telescope Axial Replacement (COSTAR) which added corrective optics to the axial instruments (Hartig et al 1993). This
5. The extra-terrestrial vacuum-ultraviolet wavelength range

Figure 5.8: Echelle spectrum of BD+28\degree 4211 recorded with the STIS FUV MAMA detector. The spectrum covers the range from 115 nm to 170 nm with a nominal resolving power of $4.6 \times 10^4$. Broad Ly\alpha absorption is seen in two echelle orders near the bottom of the format, along with numerous narrow stellar absorption lines (from Kimble et al 1998).

was achieved during the first HST servicing mission (HSM 1) in December 1993. The WFPC 2 is designed for diffraction-limited imaging at wavelengths between $\approx 120$ nm and 1.0 \(\mu\)m over a wide FOV (Rodgers and Vaughan, 1993; Trauger et al 1994). The detectors used are four contiguous $800 \times 800$ pixel CCDs with $15 \mu\text{m} \times 15 \mu\text{m}$ pixels. COSTAR improved the imaging qualities of the GHRS and the FOC (Robinson et al 1998; Jedrzejewski et al 1994).

The GHRS was replaced by the Space Telescope Imaging Spectrograph (STIS) during HSM 2 in February 1997. STIS is a complex multi-mode imaging spectrometer covering the wavelength range from $\approx 115$ nm to 1.0 \(\mu\)m (Woodgate et al 1998). Kimble et al (1998) have described the on-orbit performance of STIS. It employs a $1024 \times 1024$ pixel CCD to cover the wavelength ranges from 305 nm to 555 nm and 550 nm to 1000 nm, a $2048 \times 2048$ pixel multi-anode microchannel array (MAMA) (see Chapter 22) pulse-counting detector with a Cs Te photocathode to cover the wavelength range from 165 nm to 315 nm (near ultraviolet; NUV), and a $2048 \times 2048$ pixel MAMA with an opaque Cs I photocathode to cover the wavelength range from 115 nm to 170 nm (far ultraviolet; FUV). These large-format imaging detector systems, together with the direct-imaging, long-slit spectroscopy, and short-slit echelle spectroscopy modes, give STIS a tremendous spectral and spatial “grasp”, as shown in Figures 5.8 and 5.9.
Figure 5.9: Composite UV image of Saturn recorded with the FUV MAMA detector. Molecular hydrogen is color-coded blue, while Lyα emission, bright in the auroral zones, is color-coded red. Taken from http://opposite.stsci.edu.

The FOC was replaced with the Advanced Camera for Surveys (ACS) during HSM 3b during March 2002. ACS has three camera systems, the Wide Field Camera (WFC) and the High Resolution Camera (HRC) covering the wavelength range from 200 nm to 1100 nm, and the Solar Blind Channel (SBC) covering the wavelength range from 115 nm to 170 nm (Clampin et al. 2000; Ford et al. 2003). ACS employs a mosaic of two 2048 × 4096 pixel CCDs to give a FOV of 202″ × 202″.

Information on all of the HST instruments and observations can be found at the Space Telescope Science Institute (STScI) web site.

It was widely believed for many years that the opacity of interstellar hydrogen would make VUV observations impossible at wavelengths below 91 nm. However, the opacity decreases at shorter wavelengths and the distribution of hydrogen was found to be highly uneven. The EUVE observatory was launched in June 1992 to study the wavelength range from 7 nm to 700 nm. EUVE employed a set of grazing-incidence telescopes (Sirk et al. 1997), and variable line spacing grazing-incidence grating spectrometers (Bowyer 1997). During its lifetime, which ended in 2001, EUVE observed over 700 sources of extreme ultraviolet (EUV) radiation.12

All of the VUV astrophysics missions, with the exception of Copernicus, had lower wavelength limits around 115 nm due to the use of windows or filters. The FUSE observatory was launched in June 1999 in order to make high-resolution (λ/Δλ ≈ 2 × 104) measurements at wavelengths between 90.5 nm and 118.7 nm

12Details of the mission can be found at http://archive.stsci.edu/euve.
(Sahnow et al 2000). *FUSE* employed normal-incidence SiC optics and open-structure double delay line (DDL) microchannel plate (MCP) detectors (see Chapter 22, Timothy 2010). *FUSE* had a series of specific science objectives and also made measurements that were complementary to those of *HST* (see, e.g., Figure 5.10).13

Finally, *GALEX* was launched in April 2003. *GALEX* employs a 50 cm astigmatism-corrected Ritchey-Chrétien telescope and grisms to record imaging sky surveys in two wavelength bands in the range from 135 nm to 280 nm, and spectroscopic sky surveys in this range with a spectral resolution of $\approx 100$ (Martin et al 2003).14

**The future**

The future for solar VUV observations seems very solid at this time; *SOHO* and *TIMED* continue their observing programmes. The *STEREO* spacecraft pair has an adequate separation to continue producing unique stereo VUV images. *Hinode* is performing its observing programme, although there are some problems with the high data-rate telemetry downlink. Further, *SDO* was successfully launched by NASA on 11 February 2010 and the instruments are now undergoing on-orbit checkout in preparation for a five-year mission.15 In addition, the *Solar Orbiter* payload has been defined, including an EUV imager and a spectrometer, which will resolve Doppler shifts down to 2 km s$^{-1}$ and, by approaching the Sun down to 0.22 ua, will resolve solar spatial features to about 150 km.

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13Details of the *FUSE* mission can be found at [http://fuse.pha.jhu.edu](http://fuse.pha.jhu.edu).
14Full information on the *GALEX* mission can be found at [http://galex.caltech.edu](http://galex.caltech.edu).
In contrast, the future for astrophysics VUV missions, in the near term was, until recently, highly uncertain, and in the later future, frankly, bleak. *GALEX* continues its observing programme after five years in orbit. However, the *FUSE* mission has been terminated by the total failure of the attitude control system, STIS is currently disabled by the failure of the backup low-voltage power supply, which has closed the shutter, and the ACS has had a catastrophic failure which only permits the SBC to continue operating. Further, *HST* is currently operating on the redundant Side B of the Science Instruments Command and Data Handling system (SICDH), following the failure, after 18 years of operation, of Side A.

The near-term future has now improved dramatically following the success of *HSM4* in May 2009. The STIS and ACS instruments were repaired successfully. Also, two new instruments, namely COS (see Green et al 2003) and WFC3 (see Kimble et al 2008) were installed. Further major upgrades were made to the telescope. Six new gyros, new batteries, a new SICDH, and a new fine guidance system were installed. Finally, the thermal insulation was repaired. NASA has now started to release the full results of *HSM4* (see [http://hubblesite.org](http://hubblesite.org)). Hopefully, we can now look forward to a further five to eight years of VUV astrophysics observations with *HST*. Beyond *HST*, the future for VUV astrophysics missions remains highly uncertain.

The next generation space telescope, namely the *JWST*, is designed for observations at infrared wavelengths, and beyond that, informal proposals for future VUV astrophysics missions are being developed in the US and Europe. However, given the priorities and budget constraints of NASA and ESA, it seems unlikely that another major VUV astrophysics mission can be started before about 2015 at the earliest. It may well be that the challenge is picked up by other space-faring nations.

Acknowledgements: The research on this chapter has benefited from extensive use of the data in NASA’s Astrophysics Data System (ADS), administered by the Smithsonian Astrophysical Observatory.

**Bibliography**


Hinteregger HE, Hall LA, Schweizer W (1964) Solar XUV spectrum from 310 Å to 55 Å. Astrophys J 140:319–327
Jacchia LG (1971) Revised static models of the thermosphere and exosphere with empirical temperature profiles. Smithsonian Astrophysical Observatory SR 332
Lean J, VanHoosier M, Brueckner G (plus three authors) (1992) SUSIM/UARS observations of the 120 to 300 nm flux variations during the maximum of the solar cycle—Inferences for the 11-year cycle. Geophys Res Lett 19:2203–2206
Mason HE, Young PR, Pike CD (plus four authors) (1997) Application of spectroscopic diagnostics to early observations with the SOHO Coronal Diagnostic Spectrometer. Sol Phys 170:143–161
5. THE EXTRA-TERRESTRIAL VACUUM-ULTRAVIOLET WAVELENGTH RANGE


Timothy JG, Chambers RM, D’Entremont AM (plus two authors) (1975) A sounding rocket spectroheliometer for photometric studies at ultraviolet wavelengths. Space Sci Instrum 1:23–49


