EXTREME AND FAR ULTRAVIOLET ASTRONOMY FROM VOYAGERS 1 AND 2

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Abstract. The instrumental characteristics, observational capabilities and scientific results of the Voyager 1 and 2 ultraviolet spectrometers are reviewed. These instruments provide current and ongoing access to low resolution spectra for a wide variety of astronomical sources in the 500 to 1700 Å band. Observations of the brightest OB stars and hot subluminous stars as faint as V = 15 mag. are possible. In the EUV, at wavelengths shortward of 900 Å, several new sources have been detected and a host of potential sources ruled out. In the Far UV, particularly at wavelengths between 900 and 1200 Å, Voyager is capable of observing a wide range of stellar and non-stellar sources. Such observations can often provide a valuable complement to IUE and other data sets at longer wavelengths. The Voyager spectrometers have proved remarkably stable photon counting instruments, capable of extremely long integration times. The long integration times, relatively large field of view, and location in the outer solar system also provide an ideal platform for observations of sources of faint diffuse emission, such as nebulae and the general sky background.

1. Introduction

On board the Voyager 1 and 2 spacecraft are nearly identical ultraviolet spectrometers (UVS), sensitive over the wavelength range 500 to 1700 Å. Although designed primarily to observe extreme and far UV emission from the atmospheres of the outer planets and several of their satellites, these instruments have proved exceptionally effective at conducting a wide variety of exploratory astronomical observations at wavelengths below 1200 Å. In contrast to the X-ray and longer wavelength UV, where earth orbital observations are now well established, the EUV (100 to 900 Å) and FUV (here, 900 to 1200 Å), have received scant attention. There are still wavelength ranges under active exploration, where low resolution spectroscopy or spectrophotometry can lead to important new discoveries. Over the past decade one major means of exploring these bands has been through observations conducted with the Voyager UVS. Important aspects of stellar astronomy investigated by Voyager have included: observations of luminous OB stars, a variety of active binary systems such a cataclysmic variables, hot subluminous stars including white dwarfs, subdwarfs, planetary nebulae and PG1159 objects. Other non-stellar observations have included: supernova remnants, globular clusters, active galaxies and components of the EUV and FUV sky background. Currently, the Voyager instruments are virtually the only means of conducting routine on going observations at these wavelengths.

In this paper the important instrumental, and observational characteristics of the Voyager spectrometers are reviewed. This is followed with a brief presentation

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of several different types of observations obtained with Voyager, each illustrating one or more unique aspects of these instruments.

2. Instrumentation and Observing Capabilities

Both Voyager instruments are compact, Wadsworth mounted, objective grating spectrometers (Broadfoot et al. 1977) covering the wavelength range 500 to 1700 Å. Collimation of incoming UV radiation is accomplished with a series of precession mechanical baffles which define a primary instrumental field-of-view (FOV) of 0.10 deg ×0.87 deg (FWHM). A single normal incidence reflection from a concave diffraction grating then focuses the dispersed image on to an array detector. The grating is a platinum coated replica, ruled at 540 lines/mm, blazed at 800 Å. and having a radius of curvature of 400.1 mm. Dispersion in the image plane is 93 Å/mm. In addition to the primary FOV, each UVS has a small 20 deg off-axis port which allows direct viewing of the sun, at decreased detector gain.

The open, photon counting detector consists of a dual microchannel plate (MCP) and a 128-element linear self-scanned readout array.

For wavelengths shortward of 1250 Å, the quantum efficiency of the MCP is that of the bare glass, ~ 10%. Longward of 1250 Å, the quantum efficiency is enhanced by the use of a semi-transparent CuI photocathode deposited on a MgF_2 substrate. The MCP is normally operated at a gain of $\sim 10^6$ and its output is proximity focused onto a linear array of aluminum anodes. Each of the 128 anodes (126 active plus two dead, trailing channels) is accessed every 320 μs and its output charge passed to a charge sensitive amplifier. Amplifier output for each channel is digitally converted to a 16-bit word and summed to an internal shift register memory. Memory registers are read out by the spacecraft flight data system at various defined rates, and transmitted back to earth as log compressed 10-bit words. For the astronomical observations discussed here, the two prime data rates currently are one complete spectrum every 3.84 s or every 576 s. The UVS instruments are solar blind, have no moving parts, and have operated continuously since launch in 1977. With the singular exception of a decrease in the Voyager 1 MCP gain, due to excessive radiation induced counts during passage through the inner Jovian magnetosphere, both instruments have remained photometrically stable at better than 3% level since 1977. In-flight performance of the UVS from launch through the 1979 Jupiter encounters is reviewed in Broadfoot et al. (1981).

As objective grating spectrometers, the instruments have differing spectral resolutions for point source and diffuse sources. For stellar (point) sources spectral resolution is ~ 18 Å, while for diffuse (filled field) sources it is ~ 30 Å. Instrumental sensitivity is optimized for the 800 to 1200 Å region. Typical limiting sensitivities at 1050 Å for stellar continua are 5×10^{-13} ergs cm^{-2} s^{-1} $Å^{-1}$ for Voyager 2 and 1×10^{-12} ergs cm^{-2} s^{-1} $Å^{-1}$ for Voyager 1. On-axis integration times necessary to achieve these limits are ~ 1 day. As a practical matter, however, there is often a need to observe adjacent sky background for a comparable period of time. In addition, the average efficiency of ground station coverage must also factored in. A plot relating observed signal level at 1050 Å, the required signal-to-noise ratio, and 'total observing time' (TOT) for a stellar continuum is shown in Fig. 1. For diffuse emis-

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TABLE I
Voyager Ultraviolet spectrometers

- Optical Configuration
    - Wadsworth Mount Objective Grating
    - 22.1 cm^{-2} Platinum replica Grating, Blazed at 800 Å
    - Mechanical Collimation: 0.°10 x 0.°87 Field of View
- Photon Counting Detector
    - 128 Channel Microchannel Plate, Bare for $\lambda < 1250$ Å
    - CuI on MgF_2 Filter for $\lambda > 1250$ Å
    - Self-Scanned Aluminum Anode Array
    - Integration Times of 3.84 and 576 Seconds
    - Dark counts 2.5×10^{-3} counts s^{-1} $channel^{-1}$
- Performance
    - Spectral Range (Å):$525 < \lambda < 1650$
    - Resolution: ~ 18 Å (9.26 Å / channel)
    - Limiting Flux: $0.2\text{-}0.5 \times 10^{-12}$ ergs cm^{-2} sec^{-1} $Å^{-1}$ at 1000 Å
    - Stability: <2% Change in 3 Years
    - Absolute Calibration: ~10-15%

sion, limits of 100 photons cm^{-2} s^{-1} $Å^{-1}$ str^{-1} and 6000 photons cm^{-2} s^{-1} str^{-1}, for line and continuum emission in the 500 to 1200 Å band have been acheived, using Voyager 2 (Holberg 1986). Very long integration times, measured in days, are a normal mode of observing with the UVS. The instruments have low backgrounds, 2.5×10^{-3} counts s^{-1} $channel^{-1}$, due primarily to gamma rays from the spacecraft radioisotope thermoelectric generators and scattering interplanetary H I Lyman series and He I 584 Å emission lines.

A summary of instrumental parameters is contained in Table I.

UVS data typically consist of an extended time series of a large number (1000's) of individual spectra. To obtain a representative spectrum for stellar sources, these spectra are first placed into a spatially ordered sequence. This is necessary because of objective grating nature of the spectrometers and because they are located on a spacecraft subject to small quasi-periodic attitude control motions. The net effect of these spacecraft motions is to move the instrumental FOV with respect to the target, causing off-axis spectra to experience small wavelength shifts and vignetting due to the collimator. Spacecraft attitude control motion is computed for each spectrum from the attitude control system error signals. With this information, it is possible to correct individual spectra for off-axis effects. These spectra are then summed, background subtracted, flat fielded, corrected for scattered light and photometrically calibrated. Typical extracted stellar spectra are shown in Fig. 2. A detailed discussion of the reduction of spectral data is contained in Holberg (1986) and Longo et al. (1988).

As mentioned above, two primary data modes are currently available for the

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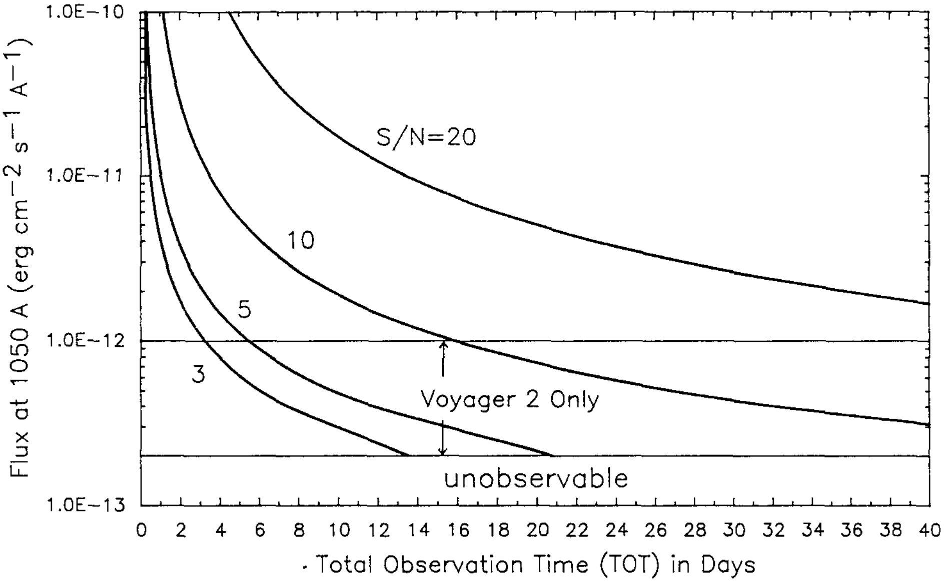

Fig. 1. Total Observing Time (TOT) vs observed flux at 1050:80 for faint objects at four signal-to-noise levels; 20, 10, 5, 3. TOT includes on-target integration time, a comparable amount of sky background integration and 50% ground station coverage.

UVS data; a high rate of 3.84 s per spectrum and a low rate of 576 s per spectrum. For observations involving stellar sources, the high data rate is preferred as it allows adequate sampling of the spacecraft limit cycle motion which has characteristic periods of ~ 20 min. Stellar observations can be achieved at the low data rate but photometric accuracy often suffers as a result of the less precise knowledge of the motion of the slit with respect to the source. Low data rate spectra are useful for diffuse sources and for obtaining sky background for stellar observations.

2.1. OPERATIONS

Each UVS instrument is located, along with the other optical remote sensing experiments, on a two-axis scan platform at the end of the spacecraft science boom. Pointing the UVS at astronomical targets is accomplished by driving the scan platform to a set of predetermined actuator angles. Scan platform pointing accuracy is typically ~ 2 arcmin, sufficient to place the target within the 0.10 deg wide UVS slit. Most areas of the sky are accessible from one or both spacecraft. A mutual obscuration zone in the southern hemisphere currently exists (see Fig. 3). In addition, scattered light hampers the observation of most targets with in 25 deg of the sun. These geometrical constraints change very slowly with time, as do slit orientations with respect to any specific target. All observations are preplanned as part of the overall spacecraft operating sequence resident in the spacecraft computer memory; no real-time operation is possible. In the near future, each spacecraft memory load

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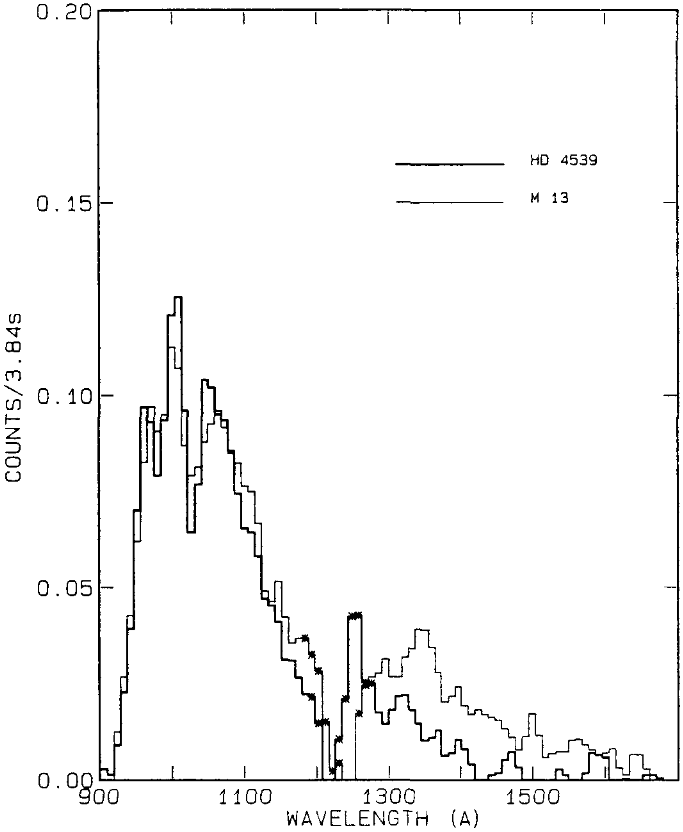

Fig. 2. A comparison of the the Voyager 2 spectrum of the integrated light from the globular cluster M 13 with a Voyager 2 spectrum of the hot sub dwarf B star, HD 4539. For this comparison the HD 4539 spectrum has been scaled to an apparent magnitude of V=11.

will operate for a 13 week period and targets will be scheduled 15 to 20 weeks in advance of the actual observation. Observations requiring simultaneous coverage of a target from the ground or another spacecraft should allow for such lead times. UVS observations, specified in simplest terms by, an initial time, right ascension, declination, and duration, are planned as part of each sequence and occur as they are clocked out by the spacecraft command and control computer. Data are received at NASA Deep Space Net ground stations, processed at the Jet Propulsion Laboratory in Pasadena and generally arrive at the Lunar and Planetary Laboratory in Tucson within one month. Ground station coverage averages between 8 to 12 hrs per day on each spacecraft.

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2.2. FUTURE PLANS

Continued astronomical observations with the UVS are currently planned to be part of the Voyager Interstellar Mission (VIM). The VIM program, which officially began on January 1 1990, has as its prime objectives:

(a) to investigate the interplanetary and interstellar media, and to characterize the interaction between the two.

(b) to continue the successful Voyager program of ultraviolet astronomy.

It is anticipated that it will be practical to return UVS astronomical data at useful rates until at least 1995 when Voyagers 1 and 2 will have reached distances of 59 and 44 AU, respectively. A substantial upgrade in telemetry performance, scheduled to occur later this year, will allow the bulk of UVS data to be returned at the high (3.84 s/spectrum) data rate preferred for point source observations. This will significantly increase observing efficiency for stellar and other localized targets. Plans call for observing up to 4 targets per week per spacecraft while in this data rate; a factor of 2 to 3 increase over what has been possible in the past. In addition to astronomical observations, a parallel program of solar observations is also planned, as are continued observations of emission form the interstellar wind and interplanetary medium.

In 1988 UVS observations were opened to an initial round of guest investigator proposals. These guest investigator observations began in late 1989, following completion of the Neptune encounter activities. They are expected to be completed later this year. Currently, NASA is considering the possibility of a second round of UVS guest investigator observations.

3. Examples of Observations Possible with VOYAGER

In the remainder of this paper some of the more unique observing characteristics of the Voyager UVS are illustrated with brief accounts of several observations.

3.1. GLOBULAR CLUSTERS

In the optical, globular clusters are dominated by red giants and sub giants. In the UV, however, such stars are intrinsically faint and cluster luminosity can be dominated by a relatively small number of hot blue stars.

Obtaining integrated spectra of this stellar population has been hampered by the relatively large angular extents of most globular clusters. The UVS slit, however, is conveniently matched to the angular diameters of many clusters. At the suggestion of Dr. Horace Smith of Michigan State University, three globular clusters wer observed with Voyager 2: NGC 6752, M 13 and M 92. In each case a hot, stellar-like spectrum extending to the Lyman limit was observed. The two strongest detections were NGC 6752 and M 13. In Fig. 2 the M 13 count rate spectrum is compared with a Voyager 2 spectrum of the well known subdwarf B star, HD 4539. It is clear from IUE observations of individual cluster stars (see Castellani and Cassatella 1987) that hot subluminous stars are responsible for the UV luminosity of globular clusters. These Voyager observations have provided the first integrated spectra of globular clusters in the FUV.

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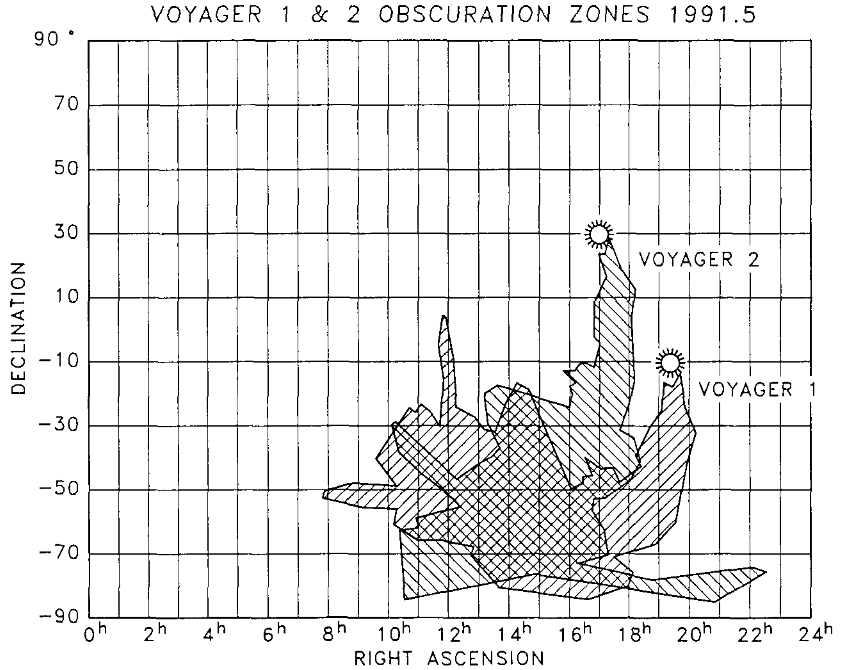

Fig. 3. Accessible regions of the sky in mid-1991, as seen from Voyagers 1 and 2. The hatched regions are portions of the sky obscured by spacecraft structure. The apparent locations of the sun as seen from each spacecraft are indicated. Scattered light becomes a problem within 25 degrees of the sun

3.2. FUV Sky Background

The availability of extremely long integration times, the relatively low amounts of foreground emission present in the outer solar system and the relatively large field of view all contribute to the effectiveness of Voyager in observing the FUV sky background. Indeed, the best current upper limits on high galactic latitude sky backgrounds between 500 and 1200:80 have been obtained form Voyager 2 (Holberg 1986). At UV wavelengths, the principal components of the diffuse sky background are expected to be star light scattered from interstellar dust and recombination line emission from ions in a possible hot (10^5 K) component of the interstellar medium.

The first of these components is a diffuse continuum having an energy distribution characteristic of the hot, early type stars which illuminate the dust. In contrast to the upper limits on sky background found by Holberg (1986) at high galactic latitudes, several low latitude regions have now been found which exhibit diffuse stellar-like continua. The most interesting of these is associated with a 150 day long drift of the Voyager 2 FOV through the constellation of Ophiuchus. In these data a diffuse continuum extending over many degrees and having a mean 1000 Å intensity of 2500 photons cm^{-2} s^{-1} $Å^{-1}$ str^{-1} was observed. Spectra of this emission bear a strong resemblance to a single modestly reddened O star of 11 mag. Figure 4 shows

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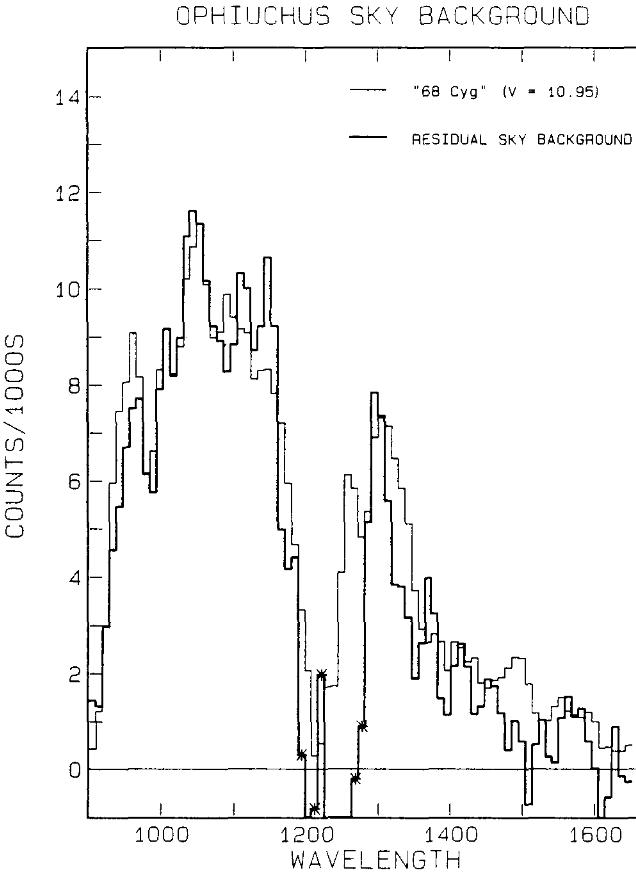

Fig. 4. A comparison of the observed spectrum of the diffuse background observed in Ophiuchus with an observation of the moderately reddened O8 star; 68 Cyg. The 68 Cyg spectrum has been uniformly reduced by a factor corresponding to 5.95 magnitudes

this spectrum compared with a Voyager 2 spectrum of 68 Cyg (O8, B–V = –0.01). The interpretation (Holberg 1990) is that this is due to the scattering of FUV starlight from interstellar dust; in effect an extended reflection nebula is being observed.

3.3. INTERSTELLAR REDDENING

In sharp contrast to longer wavelengths, knowledge of interstellar reddening shortward of 1200 Å has remained in rudimentary state. Virtually the only direct observations are those of York et al. (1973) who used Copernicus to obtain reddening four curves for wavelengths down to 1000 Å. Recently, however, Snow, Mason and Polidan (1990) have used Voyager UVS observations to greatly expand reddening studies to include many more reddened-unreddened pairs and to extend wave-

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length coverage 950 Å. This study indicates that reddening raises steeply between 1200 Å and 950 Å, as expected from theoretical studies. In addition, as is the case at longer wavelengths, considerable variation is seen among extinction curves. These studies were made possible through the use of the extensive archive of Voyager observations of luminous OB stars.

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