ULTRAVIOLET SKY SURVEYS

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1. Introduction

Among all spectral bands, the ultraviolet has long been neglected, despite the advantage of small space experiments: the sky is very dark, thus detection of faint objects does not compete against an enhanced background (O'Connell 1987) and the telescope construction techniques are very similar (at least longward of ~50 nm) to those of optical astronomy.

The short history of UV astronomy can be divided into two eras, until the flight of TD-1 and since the availability of the TD-1 all-sky survey. Very little was accomplished in terms of general sky surveys during this second era. The UV domain may be divided into the "regular" ultraviolet, from shortward of the spectral region observable from ground-based observatories (~320 nm) to below the Lyman break at ~80 nm, and the region from the Lyman break to the fuzzy beginning of the X-ray domain, arbitrarily defined as ~6 nm≈200 eV). The first segment is called "UV" and the second "extreme UV" (EUV). Observational techniques used in the EUV are more similar to those in X-ray astronomy, whereas the UV is more like the optical.

The units used here are "monochromatic magnitudes," defined as:

$$m(\lambda) = -2.5 \log[f(\lambda)] - 21.175 \tag{1}$$

where f(λ) is the source flux density in erg sec^{-1} cm^{-2} $\mathrm{\AA}^{-1}$, at wavelength λ. The background brightness is described in "photon units" (c.u.=count units) which count the photon flux in a spectral band, per cm^2, per steradian, and per Å. At 150 nm, 1 c.u.=1.32 10^{-11} erg cm^{-2} sec^{-1} $\mathrm{\AA}^{-1}$ $\mathrm{steradian}^{-1}$, or 1.32 10^{-13} W m^{-2} nm^{-1} $\mathrm{steradian}^{-1}$, or 32.6 mag arcsec^{-2}.

Although only few missions performed full sky surveys in the UV or EUV, many scanned or imaged restricted sky regions and provided information about the deeper UV sky. O'Connell (1991) reviewed UV imaging experiments and their results updated to 1990.

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In parallel with the development of UV astronomy, first steps were taken to study the EUV sky. Detections in the EUV range are hampered by the opacity of the interstellar medium (ISM). From 91.2 nm shortward to about 10 nm the opacity is high, because of the photoelectric cross-section of H^0, and to a lesser extent of He^0 (below 50.4 nm) and He^{+1} (below 22.8 nm).

The first studies in the EUV range were with rocket-flown instruments (Henry *et al.* 1975 a, b, c), which measured a few very bright sources and established calibrators. The earliest observations below Lyman α were by Belyaev *et al.* (1971). The culmination was the EUV instrument flown on the Apollo-Soyuz mission in 1975, when four EUV point sources were discovered (Lampton *et al.* 1976, Margon *et al.* 1976, Haisch *et al.* 1977, Margon *et al.* 1978). The Voyager spacecraft explored the EUV sky with their Ultraviolet Spectrometers (UVS: Sandel, Shemansky and Broadfoot 1979). For a number years the two Voyager spacecraft were the most distant astronomical observatories (Holberg 1990, 1991).

2. The TD-1 Era

Modern UV astronomy began with the first UV all-sky survey by the ESRO **TD-1** satellite, described by Boksenberg *et al.* (1973). The all-sky catalog of UV sources was published by Thompson *et al.* (1978) with 31,215 stars with S/N>10 in all four TD-1 bands. An unpublished version, with lower S/N, has 58,012 objects. The TD-1 S2/68 experiment is a benchmark against which all other sky surveys are and will be measured.

After TD-1, the various UV and EUV efforts can be characterized as either imagers or spectrometers. Among the imagers, some were orbiters and others were on short-duration flights. Some major missions were ANS and IUE. **ANS** was described by Van Duinen *et al.* (1975), Wesselius *et al.* (1982), and de Boer (1982). One of the greatest successes of any orbiting astronomical instrument was the **IUE** observatory (Boggess *et al.* 1978). The IUE data are a valuable resource, mainly after the final reprocessing of all the low-dispersion spectra into the final Uniform Low-Dispersion Archive (ULDA).

The NRL experiment **S201** was described by Page *et al.* (1982) and operated automatically on the Moon during the Apollo 16 mission in April 1972. Ten 20° diameter fields were observed, the experiment covering ~7% of the sky. The results were discussed by Carruthers and Page (1976, 1983, 1984a, 1984b). Two experiments flew on sounding rockets. **GUV** flew on 21 February 1987 and is described by Onaka *et al.* (1989). The GUV observations were re-analyzed by Kodaira *et al.* (1990). The **UIT prototype** flew on a number of rocket flights and with different focal plane assemblies. Bohlin *et al.* (1982) described the instrument and its observations of the Orion nebula. Other observations are described by Smith and Cornett (1982), Smith *et al.* (1987), and Bohlin *et al.* (1990).

UV observations from balloon-borne telescopes at 40+ km were performed by a collaboration between the Observatoire de Geneve and the Laboratoire d'Astrophysique Spatiale of Marseille. The stabilized gondola (Huguenin and Magnan 1978) carried telescopes tuned for imaging observations in a bandpass centered at ~200 nm and ~15 nm wide. **SCAP-2000** was described by Laget (1980), Donas *et al.* (1981), and Milliard *et al.* (1983). The results were published by Donas *et al.* (1987) and Buat *et al.* (1987, 1989). **FOCA** is a 39 cm diameter telescope (Milliard *et al.* 1991) which surveyed some 70 sq. degrees of the sky to ~19 mag. Results were reported by Laget *et al.* (1991a, 1991b), Vuillemin *et al.* (1991), Courtes *et al.* (1993), Buat *et al.* (1994), Bersier *et al.* (1994), Reichen *et al.* (1994), Donas *et al.* (1995), and Petit *et al.* (1996). Galaxy counts and color distributions for objects in the range 15.0–18.5 mag were published by Milliard *et al.* (1992) and used to predict UV galaxy counts (Armand and Milliard 1994).

The **Wide-Field UV Camera** flew in December 1983 on the Space Shuttle and produced some very wide-field UV images (Courtes *et al.* 1984). The NRL group headed by Carruthers flew a number of far-UV wide-field imagers on rockets (Carruthers *et al.* 1980). These flights used the Mark II **FUVCAM** (Carruthers *et al.* 1993, 1994) which flew on the Space Shuttle in spring 1991. The results were published in a series of papers dealing with individual fields (Schmidt and Carruthers 1993a, 1993b, 1995). The 40 cm telescope **GLAZAR** operated on the Mir space station (Tovmassian *et al.* 1988, 1991a, 1991b) and results were reported by Tovmassian *et al.* (1993a, 1993b, 1994, 1996a).

FAUST is the Fusee Astronomique pour l'Ultraviolet Spatiale, or the Far Ultraviolet Space Telescope, first described by Deharveng *et al.* (1979). On SPACELAB-1 in 1983 FAUST did not obtain significant data because of high on-orbit background (Bixler *et al.* 1984). During the second flight, on board the Shuttle Atlantis in March 1992 (Bowyer *et al.* 1993), FAUST observed 22 regions ~ 8° in diameter and produced a catalog of 4,698 UV sources (Bowyer *et al.* 1994a). Selected results from the FAUST imagery are by Deharveng *et al.* (1994), Haikala *et al.* (1995), and Courtes *et al.* (1995). A program of systematic investigation of FAUST images takes place the Tel Aviv University and include optical observations from the Wise Observatory. To date, we analyzed completely four FAUST fields, the North Galactic Pole (Brosch *et al.* 1996a) and three fields covering Virgo (Brosch *et al.* 1996b).

The Ultraviolet Imaging Telescope (**UIT**) was described by Stecher *et al.* (1992). It flew on the Space Shuttle during the ASTRO-1 (December

1990) and ASTRO-2 flights (March 1995). First results were published in a dedicated publication (1992 Astrophys. J. Lett. **395**). Other results are in Hill *et al.* (1993, 1994, 1995a, 1995b, 1996). The UIT source catalog (Smith *et al.* 1996) covers 16 sq.degrees of the sky and contains 2244 objects from 48 pointings in the ASTRO-1 flight.

Attempts to measure the diffuse UV background consist of many observations with wide-field instruments. Notable among these are the two Shuttle-borne UVX instruments from JHU and Berkeley (Murthy *et al.* 1989; Hurwitz *et al.* 1989). In addition, observations done for other purposes were used to derive the UV background, *e.g.*, Waller *et al.* (1995).

3. Modern EUV observations

The EUV sky was explored by the **EUV Wide Field Camera** on the ROSAT X-ray all-sky survey satellite described by Pounds and Wells (1991). The first EUV all-sky survey was during 1990–1991 (Pye 1995). Initial results were reported by Pounds *et al.* (1993) as the WFC Bright Source Catalog (BSC). The reprocessed data make up the 2RE catalog (Pye *et al.* 1995) with 479 EUV sources. In 2RE 52% of the sources are active F, G, K, and M stars, 29% are hot white dwarfs, and less than 2% are AGNs.

The region bordering the EUV and the X-rays was explored by the **ALEXIS** spacecraft (Priedhorsky 1991). The first sky maps were produced on 4 November 1994. The ALEXIS team calculated that $\sim$10% of the brightest EUVE sources (see below) should be detectable. Most sources are WDs; the catalog from the first three years of operation will probably contain $\leq$50 sources.

The EUV sky was investigated by the Extreme Ultraviolet Explorer (**EUVE**) spacecraft (Bowyer and Malina 1991). EUVE mapped the sky in four spectral bands, from 7 to 70 nm (18 to 170 eV). The first results were published as "The First EUVE Source Catalog" (Bowyer *et al.* 1994) with 410 sources. The Second EUVE Source Catalog (2EUVE) has recently been published (Bowyer *et al.* 1996). The majority of the identified sources in 2EUVE (55%) are G, K, and M stars.

A new catalog, to $\sim$60% of the thresholds of the second EUVE catalog, has been produced by Lampton *et al.* (1996) with 534 coincident sources between the EUVE 10 nm list and the ROSAT all-sky survey sources detected in the broadband event window (0.1–2 keV), of which 166 were not previously discovered. Of these, 105 have been identified and 77% of them are late-type stars. White dwarfs and early-type stars make up only 14% of the sources, and there are no extragalactic objects at all.

4. Comparison of Survey Missions

The various missions surveying the UV sky can be compared in terms of a "power" parameter θ, introduced by Terebizh (1986), used by Lipovetsky (1992) in a comparison of optical surveys, and slightly modified here:

$$\theta = \frac{\Omega}{4\pi} 10^{0.6(m_L - 10)} \tag{2}$$

where Ω is the sky area covered by the survey (4π for TD-1) and m_L is the limiting magnitude of the survey.

The various parameters relevant to the missions discussed here are collected in Tabel 1. An all-sky survey to $m_L \approx 8.5$ (such as TD-1) has the same "survey power" as one HST WFPC-2 image exposed to show $m_{UV}=21$ objects. Because of this, and because not all surveys cover the entire sky, it may be more useful to look at another estimator, the density of sources detected (or which are expected to be detected) by a certain experiment. This estimator indicates that the field of UV astronomy retains its vitality; the source density increases exponentially with time.

5. The Resultant Sky Picture

The combined results yield a picture in which most of the stars detected by TD-1, FAUST, SCAP and FOCA are early-type B, A and F. However, most of the stars included in the UIT catalog are probably late-type (G and later). In the FAUST fields where the reduction and identification processes are complete, we find almost equal fractions of A–F stars (70 and 75%). Except for the fields studied at Tel Aviv (Brosch *et al.* 1995, 1996), most surveys used exclusively correlations with existing catalogs to identify sources. These sometimes mis-identify objects, as some likely early-type stars are just below the catalog thresholds.

The UV information on galaxies is very sparse and a statistically complete sample of a few 1000's galaxies is lacking. In the absence of very deep surveys in more than a single spectral band, our information about a significant number of galaxies originates from SCAP-2000 (Donas *et al.* 1987) and FOCA (Milliard *et al.* 1992). These measurements consist of integrated photometry at 200 nm of a few hundred galaxies. In the range 16.5–18.5 mag galaxies dominate the source counts at high $|b|$. These have B=18–20 and $[2000\text{-}V] \approx -1.5$. Using the "field" galaxy luminosity function in the UV from Deharveng *et al.* (1994) the differential number density is:

$$\log N(m) = 0.625 \times m_{200} - 9.5 \tag{3}$$

Studies by UIT and FAUST emphasize the importance of the dust in understanding the UV emission. Bilenko and Brosch (1996) analyzed the

TABLE 1. UV and EUV survey missions

Mission	Year	Ω (ster)	m_L	θ	$\lambda\lambda$ (nm)	$N_{sources}$	Notes
TD-1	1968–73	4π	8.8	0.19	150–280	31,215	1
S201	1972	0.96	11	0.30	125–160	6,266	
WF-UVCAM	1983	1.02	9.3	0.03	193	?	
SCAP-2000	1985	1.88	13.5	18.9	200	241	2
GUV	1987	$5\ 10^{-3}$	14.5	0.2	156	52	3
GSFC CAM	1987+	0.03	16.3	14.4	242	~200	4
FOCA	1990+	0.02	19	377	200	~4,000	5
UIT-1	1990	$3.8\ 10^{-4}$	17	0.48	~270	2,244	6
GLAZAR	1990	$4.4\ 10^{-3}$	8.7	$6\ 10^{-4}$	164	489	
FUVCAM	1991	0.09	10	$7.5\ 10^{-3}$	133, 178	1,252	7
FAUST	1992	0.33	13.5	3.3	165	4,698	
UIT 1+2	1990, 95	$1.3\ 10^{-3}$	19	26	152–270	6,000 ?	8
HST WFPC	1990+	$3.9\ 10^{-4}$	21	123	120–300	50,000 ?	9
MSX UVISI	1997+	4π ?	13.9	218	180–300	?	
GIMI	1997+	4π	13.6	136	155	$2.5\ 10^5$	10
TAUVEX	1998+	0.06	19	11,700	135–270	10^6	11
WFC	1992 ?	4π	-	-	10, 16	479	
ALEXIS	1994+	4π	-	-	13–19	50?	
EUVE	1992 ?	4π	-	-	7–70	734	12

Notes to Table 1:
1: The unpublished extended version has 58,012 sources.
2: 92 stars (Laget 1980) and 149 galaxies (Donas *et al.* 1987).
3: Pointed phase.
4: Virgo observation.
5: Estimated.
6: UIT Catalog.
7: Only the Sag and Sco fields (Shuttle flights) included.
8: Assumes 66 pointings for ASTRO 1 and 100 for ASTRO 2.
9: Assumes 1000 observations with HST with UV filters on WFPC-2.
10: Assumes 2× stars per magnitude w.r.t. TD-1.
11: Assumes 5000 independent pointings to end-of-life.
12: Number of sources in the 2nd EUVE catalog.

TD-1 catalog and a version of the Hipparcos Input Catalog transformed to the TD-1 bands and showed that the UV exinction is very patchy, with different extinction gradients on scales $< 10°$. Tovmassian *et al.* (1996b) used GLAZAR observations of a 12 degree^2 area in Crux to establish that the dust distribution is very patchy, with most of the space relatively clear of dust. The EUVE catalogs (Bowyer *et al.* 1994, 1996; Lampton *et al.*

1996) confirm the previously known features of the local ISM (a "tunnel" to CMa with very low HI column density to 200 pc and close to the Galactic plane, a cavity connected with the Gum Nebula in Vela, a shorter 100 pc tunnel to 36 Lynx, and the very clear region in the direction of the Lockman hole).

The accurate measurement of the UV sky background (UVB), with the expectation that it could set meaningful cosmological limits, has been the goal of many rocket, orbital, and deep space experiments. Observational results were summarized by Henry (1982), Bowyer (1990), Bowyer (1991), and Henry (1991). The various origins of the UVB can be separated into "galactic" and "high latitude." The latter is an ~uniform pedestal, onto which the former is added in various amounts depending on the direction of observation. The "galactic" component can be ~one order of magnitude more than the "high latitude" one. Most is probably light scattered off dust particles in the ISM and the rest is from the gaseous component of the ISM (HII two photon emission and H_2 fluorescense in molecular clouds). The "high latitude" component is also mostly galactic, light scattering off dust clouds at high $|b|$.

The extragalactic component of the UVB (eUVB) can be at most 100–400 c.u. (Murthy and Henry 1995). Whenever $N(HI)>2\ 10^{20}$ cm^{-2}, the main contributor is dust-scattered starlight. The low level eUVB is probably integrated light of galaxies (Armand *et al.* 1994), or Milky Way light scattered off dust grains in the Galactic halo (Hurwitz *et al.* 1991), or intergalactic Lyα clouds contributing their recombination radiation (Henry 1991).

The low UVB away from orbital and galactic contaminants has recently been confirmed by ASTRO-1 UIT images (Waller *et al.* 1995). After correcting for orbital background and zodiacal light, and after accounting for scattered Galactic light by ISM cirrus clouds (from the IRAS 100 μm emission), the extrapolated UV-to-FIR correlation to negligible FIR emission indicates $[eUVB]\approx 200\pm 100$ c.u.

The shorter wavelength UVB has been observed with the Voyager UVS down to 50 nm (Holberg 1986). A very deep EUVE spectroscopic observation of a large region on the ecliptic has recently been reported (Jelinsky *et al.* 1995) but the only emission lines observed were He I and He II (58.4, 53.7, and 30.4 nm), which originate from scatted Sunlight by the geocoronal and/or interplanetary medium and no continuum was detected.

The "true" eUVB can be evaluated from the FOCA data (Milliard *et al.* 1992). The galaxy counts, for $15.0\geq m_{200} \geq 18.5$, extrapolated to $m_{200}=20.0$, give a contribution of ~100 c.u.'s from only UV galaxies. Milliard (1996, private communication) studied the nature of sources in the

A2111 FOCA field. The majority are emission-line galaxies, only 16% in A2111 and the rest are in the foreground or background up to z≈0.7.

The detection and identification of faint UV galaxies may help resolve the issue of a real eUVB. Recent indications are that the eUVB is negligible. Waller *et al.* (1995) estimated 200±100 c.u. in the UIT near-UV band. Unpublished results from an analysis of 17 years of Voyager UVS spectra (Murthy *et al.* 1996, in preparation) indicate that at ~100 nm the UVB is $\leq$100 c.u. (1σ). However, when adopting the FOCA galaxy counts and extrapolating to m_{UV}=20 and to ~1000Å using the SEDs of starburst galaxies from Kinney *et al.* (1996), the contribution due to sources unresolved by UVS violates the Murthy *et al.* limit. An extrapolation to m_{UV}=23 violates also the UIT constraint. It is therefore necessary to investigate the faint end of the UV galaxy distribution to understand the nature and reality of the eUVB.

6. The Future

Two UV missions are approved, funded, built, and integrated into their carrier spacecraft. These are the UVISI on MSX, and GIMI on ARGUS, which will produce full or partial UV sky surveys. MSX was launched on 24 April 1996 and the operation of UVISI is expected to start in 1997. ARGUS has been slightly delayed and will be launched in 1997.

The narrow field UV imager of **UVISI** (Heffernan *et al.* 1996) is sensitive to sources which produce 2 photons cm^{-2} sec^{-1}, *i.e.*, m_L ≈13.9 (monochromatic, at 240 nm). It is not clear how much of the sky will MSX survey. However, **GIMI** on ARGOS has as a declared goal the production of a full sky survey in three UV bands. The most recent description of GIMI (Carruthers and Seeley 1996) indicates m_L ≈13.6.

TAUVEX, **T**el **A**viv University **UV** **Ex**plorer, (Brosch *et al.* 1994) is the most advanced attempt to design, build and operate a flexible instrument for observations in the entire UV band. TAUVEX images the same $0\overset{\circ}{.}9$ FOV with three co-aligned telescopes with an image quality of about 10″. It is part of the scientific complement of the Spectrum X-γ spacecraft. The projected performance is detection of objects 19 mag and brighter with S/N>10 in three bands ~40 nm wide, after a four hour pointing. At high |b|, each pointing is expected to result in the detection of some tens of QSOs and AGNs (mainly low-z objects) and some hundreds of galaxies and stars. A three-year operation will cover ~5% of the sky to m_{UV} ≈19 mag.

The deepest observations of the UV sky should be made far from the Earth's geocorona, away from the Sun, and out of the ecliptic. Multipurpose missions to the outer planets could be used for astronomy during their cruise phase. Much cheaper options are UV observations from long-duration super-pressure balloons at 40–45 km altitude, for flights of weeks to months, with real-time operation using the TDRSS data relay satellites (Israel 1993). The reactivation of the GLAZAR telescope should be considered. An interesting possibility is to conduct a deep UV survey of a very small fraction of the sky with the HST, to learn about the faintest UV sources, beyond the capability of UIT, FOCA, or TAUVEX.

7. Conclusions

A review of the UV and EUV sky reveals that while most UV sources are early-type stars, most EUV sources are late-type stars. It is clear that UV and EUV observations are hampered by ISM opacity. Very faint UV sources are mostly galaxies, and the UVB, if it exists, is very faint and may be fully explained by galaxies.

Significant improvement in our knowledge of the UV sky can be achieved through judicious use of multi-purpose platforms, where the UV science piggy-backs on other spectral ranges. The heritage of past missions should be fully realized before embarking on new adventures. In this light, the extension of the EUVE mission in a low-cost mode is commendable; the extension of the right-angle surveys should bring in more faint EUV sources.

What science needs is either a multi-spectral all-sky UV imaging survey to 19–20 monochromatic magnitude, or a combination of cheaper alternatives, including a long-duration, very high-altitude balloon with a FOCA-type telescope and with a high-resolution detector with electronic readout for a sky survey in the 200 nm band, combined with the reactivation of the GLAZAR telescope after the status of its optics has been reassessed, with a modern, digital, photon-counting detector, and a mini-survey with HST in the UV. Additionally, an extended EUV all-sky survey, $\sim 100\times$ more sensitive than EUVE and with better angular resolution, is still required.

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