Ultraviolet Astronomy

Ultraviolet astronomy is the study of the electromagnetic radiation emitted by celestial bodies in the ultraviolet (UV) wavelength range, a portion of the spectrum simultaneously shielded by our own atmosphere and beyond the sensory limits of our sight.

Actually, the electromagnetic 'window' accessible to ground-based observers is quite limited, being virtually confined to the wavelengths the human eye is responsive to. In particular, the shielding effect of the EARTH'S ATMOSPHERE on the radiation coming from space becomes very high at wavelengths shorter than 320 nm, the adopted limit of the ultraviolet region of the spectrum. This phenomenon, mainly due to the absorption of oxygen and ozone, affects the entire UV and x-ray spectral regions, thus preventing astronomers from recording not only high energy phenomena giving origin to x- or γ-rays, but also common processes (as the thermal emission from hot stars) involving intermediate energies and producing mainly UV radiation.

This obstacle could be overcome only when—starting in the 1960s—it became possible, by means of rockets and orbiting vehicles, to carry astronomical telescopes above the bulk of the atmosphere.

The usual way of splitting the UV domain includes the so-called 'regular' UV covering the region from the atmospheric limit down to the 'Lyman break', i.e. the limit of the hydrogen Lyman line series at ~90 nm, followed by the segment from the Lyman limit to the beginning of the x-ray portion of the spectrum, arbitrarily adopted at $\lambda \sim 6$ nm (or ~200 eV, in the x-ray nomenclature). The latter region is generally referred as the 'extreme UV' (EUV), while the regular UV is often conventionally separated into far-UV (91.2–121.6 nm) plus (classical) UV and near-UV, shortward and longward of 200 nm, respectively.

The advantage of finally accessing the UV range was at least threefold. Firstly, as already pointed out, the majority of radiation emitted by stars whose photospheric temperature exceeds 10 000 K falls in the UV region. The reason is that stars' energy distribution crudely follows the Wien's law for an ideal radiator

$$\lambda_{\max} T = \text{constant} \qquad (1)$$

(where $\lambda_{\max}$ is the wavelength of maximum emission and T the temperature), thus showing the emission peak at shorter wavelengths as the temperature increases. As a consequence, one has to access the UV to properly establish the flux distribution of the hottest stars as well as their total energy output. The astrophysical relevance of such an issue (especially for STELLAR EVOLUTION matters) can be fully appreciated when modelling the spectral energy distribution of newly formed STELLAR POPULATIONS. As shown in figure 1, their emission peaks steadily in the UV from the time of the starburst onset till an age of ~300 million years, when eventually the hottest young stars disappear and the maximum emission moves longward of ~300 nm, into the visible region of the electromagnetic spectrum. Moreover, specific classes of stars experiencing hot phases *late* in their evolution (i.e. after completing their hydrogen-burning stage) emit mostly UV light.

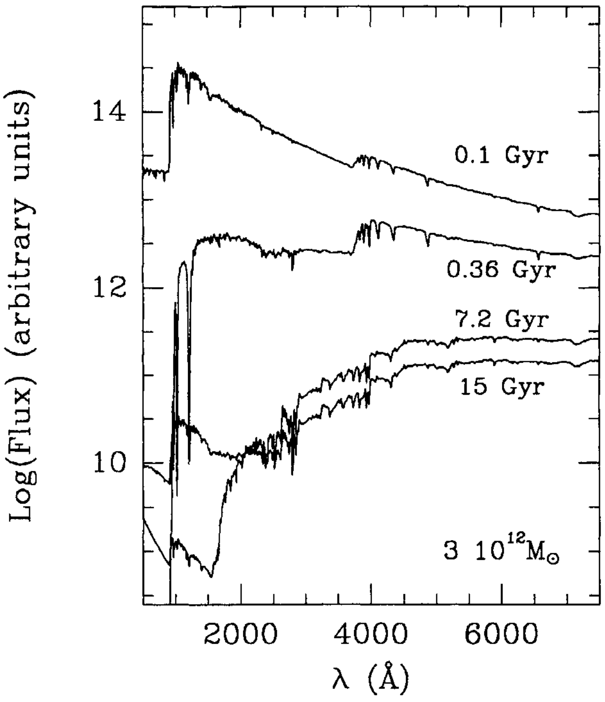

Figure 1. Integrated spectral energy distribution in the wavelength range 1000–7000 Å (100–700 nm) of a model high-mass elliptical galaxy as a function of age. Models span the whole galaxy evolution from early (100 million years) to present-time (15 billion years) phases. Note the progressive shift of maximum emission towards longer wavelengths as the most luminous, blue young stars gradually vanish. The relative rise of UV emission shortward of 200 nm at very late phases has to be ascribed to the contribution of hot, low-mass stars in metal-rich populations (from Bressan *et al* 1994 *Astrophys. J. Suppl.* **94** 63).

Secondly, UV observations represent a superb research tool to investigate both physics and chemistry of astronomical bodies owing to the occurrence, in this wavelength range, of the so-called resonance spectral transitions, i.e. the most intense, ground-state transitions for most common atoms, ions and molecules. In this respect one should stress that UV spectroscopy provides a unique observational basis to characterize the solar-like activity of cool stars (i.e. the energetic phenomena that occur in their outer atmosphere, from low chromosphere up to the chromosphere–corona transition region).

Finally, when moving to UV, one can carry out deep surveys at significantly reduced levels of sky background. Actually, space observations, besides offering an advantage over the ground which amounts to ~1 mag arcsec^{-2} at visual wavelengths (400–600 nm), provide a sky background 40× darker than at any wavelength from the ground at 200 nm (see figure 2). This

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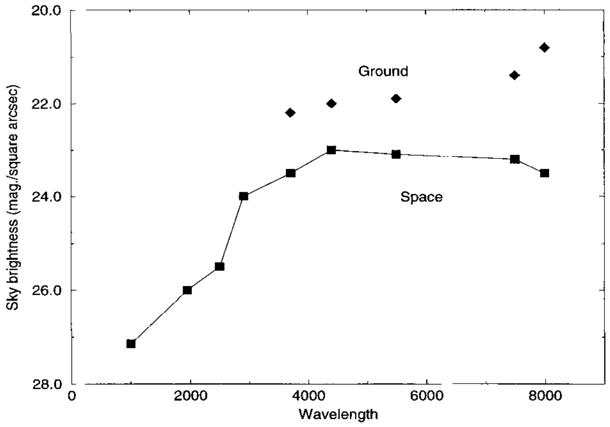

Figure 2. UV/optical night-sky background surface brightness as recorded from ground and space-borne telescopes (from Brosch 1999 *Exp. Astron.* **9** 119). Wavelength is given in Å (1 Å = 0.1 nm). Note the drop of sky brightness level in the UV.

is obviously particularly valuable when observing faint, extended sources such as distant galaxies.

One should not forget, however, that orbiting UV experiments are also influenced by specific background sources, namely the Earth AIRGLOW and polar AURORA as well as UV emission lines such as the far-UV hydrogen Lyα. Such a feature—ubiquitous within the solar system owing to the resonant scattering of solar photons off both interplanetary hydrogen and interstellar hydrogen flowing through the interplanetary space—includes a particularly strong 'geocoronal' component, i.e. the Lyα resonant scattering produced off hydrogen atoms in the halo surrounding the Earth. As a consequence, unlike other sources such as the neutral oxygen OI 130.2 nm and 135.6 nm emission lines which affect only observations at low orbital altitudes, the geocoronal Lyα heavily interferes with UV observations obtained also by intermediate and high-orbit (geosyncronous) satellites.

The dawn of UV astronomy

The technological development inherited from World War II, especially in the field of long-range ballistic weapons, made it possible to get rocket-borne payloads above the atmosphere starting in the late 1940s. In particular, the first, unguided experiments flown by the US NAVAL RESEARCH LABORATORY (NRL) on board captured German V2 rockets returned unique information on the intensity and spectral distribution of the UV emission of the Sun. Space solar astronomy is indeed less demanding in terms of instrumentation sensitivity and rocket attitude control systems, and, as such, forced early UV astronomy to start as *solar* UV astronomy.

The rate of progress of UV space astronomy was quite fast, however. Actually, very simple, single-band UV photometers, flying on-board unstabilized US Aerobee rockets were already able to provide the first UV observations of *non-solar* objects in 1950s. More exactly, the first UV data collected in the space were broad-band ($\Delta\lambda$ = 35 nm) flux measurements at 270 nm of half a hundred early-type (i.e. hot) stars. UV spectrophotometric data were obtained for the first time a few years later (1961) by means of a scanning objective grating spectrometer flying again on-board an Aerobee rocket, while the acquisition of true spectra of pre-selected individual stars had to be postponed until 1965, when three-axis stabilization systems could be implemented on rockets.

Though hampered by the very limited observing time available (a few minutes per flight), these pioneering observations (recorded on film to be collected after parachute landing) led to a revision of the temperature scale for hot stars and allowed astronomers to begin the study of mass loss phenomena from supergiants stars as well as to identify the UV interstellar absorption lines.

Instrumentation

Although UV radiation is neither transmitted nor reflected by optical components as efficiently as visible light and infrared (IR) wavelengths, the telescope construction techniques adopted to record the UV portion of the spectrum are still basically the same as those used in ground-based optical astronomy, consisting of parabolic–hyperbolic mirror combinations. One exception to this rule is the EUV waveband, as the observational techniques used in this wavelength range are more similar to those of x-ray astronomy. More precisely, observations in this range cannot make use of normal-incidence optics and the geometry of EUV telescopes has to ensure reflection via grazing incidence. In order to provide a satisfactory standard reflection of UV radiation down to $\lambda \approx 100$ nm surfaces are usually made of aluminum overcoated by MgF_2 (or LiF). High-efficiency normal-incidence reflection at shorter wavelengths, fulfilling the need of accessing the region shortward of the Lyman limit, can instead be reached by SiC mirror coatings.

As far as detectors are concerned, the present large availability of silicon CHARGE-COUPLED DEVICES (CCDs), capable of recording photons over a very wide wavelength range (from 0.1 to 1000 nm), is appealing also in view of possible applications in the UV field. Such detectors are indeed the standard choice in many areas of today's astronomy and, together with MICROCHANNEL PLATE (MCP) DETECTORS (see below), are currently replacing obsolete photographic emulsions to record UV observations, too. In this respect one should note that, of recent missions, only the Shuttle-based Ultraviolet Imaging Telescope UIT still hosted image intensifiers/converters coupled with photographic films.

When used as UV detectors, CCDs suffer from some limitation, however. Frontside-illuminated CCDs are insensitive to wavelengths shorter than 400 nm, for instance, though a better performance in the UV can be obtained by resorting to thin, back-illuminated chips. Moreover, a widespread practice intended to reach a suitable level of detective quantum efficiency (DQE, i.e. the fraction of detected photons out of those reaching the

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detector) is to apply a fluorescing phosphor coating layer a few hundred nanometers thick, able to 'down convert' UV light, i.e. to absorb wavelengths shorter than 420 nm and re-emit their energy in the visible region (around 520 nm). The largest field of view ($\approx$ 2′.5 × 2′.5) presently available to UV observers comes indeed from a mosaic of coated chips forming the UV-sensitive detector of the Wide Field Planetary Camera 2 (WFPC2) on board the HUBBLE SPACE TELESCOPE (HST).

Unfortunately detector efficiencies are further reduced by a restriction needed in UV astronomy, namely the requirement of rendering the device 'solar blind', i.e. insensitive to the—usually overwhelming—visible light coming from astronomical sources. To this aim one has to place in front of the detector specific filters which, in turn, absorb UV photons and can leave an ultraviolet DQE as low as 1–3%. Finally, one should take into account that the UV performance of CCDs even in the vacuum of space is progressively lowered by materials condensing on their surfaces; a similar phenomenon also affects the satellite optics, as tiny layers of molecular contaminants heavily absorbing UV radiation can settle over telescope mirrors.

Alternative, CCD-based UV detectors are the so-called electron-bombarded CCD cameras, which can be seen as an improvement of older electronographic cameras. The electrons released from a UV-sensitive photocathode are accelerated to high energies before impacting a solid state detector where they create many electron–hole pairs. The first-generation spectrographs of HST, such as the Faint Object Spectrograph (FOS) and the Goddard High-Resolution Spectrograph (GHRS) made use of such detectors.

A step forward in UV light detection is now assured by recently made available microchannel plate detectors. MCPs consist of a thin disk of a lead-oxide glass crossed by many microscopic channels which act as individual photomultipliers and make the detector as a whole an image intensifier, when an electric potential is applied to its faces. They represent excellent 2D detectors for the UV and EUV, when coupled with position-sensitive anodes which act as readouts.

Photon-counting MCP-based detectors cope efficiently with many drawbacks of currently available CCDs, such as finite readout noise, limited UV response and slow data access. This is the case of the state-of-the-art MAMA (Multi-Anode Microchannel Array) detectors belonging to the Space Telescope Imaging Spectrograph (STIS), the most advanced UV-sensitive instrument presently operating on board HST.

STIS does include two such detectors together with an additional CCD detector in order to optimize the telescope performance into the visible and infrared (see figure 3). The combination of the two MAMAs, whose sensitive wavebands slightly overlap (115–170 nm and 165–310 nm, respectively) ensure solar-blind, photon-counting capability together with high spatial resolution imaging.

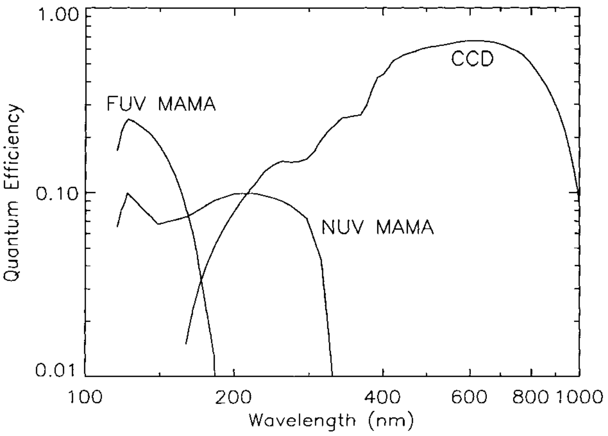

Figure 3. Superimposed quantum efficiencies of the STIS detectors. The simultaneous presence of a CCD and two distinct near-UV and far-UV MAMA detectors with overlapping sensitivities does assure a high efficiency over the whole instrument's observing range, namely 115–1000 nm (from Kimble 1997 *HST Calibration Workshop*, eds S Casertano *et al* (STScI), p 8).

UV imaging and surveys

Though UV-sensitive facilities have brought unprecedented insights into many, largely unexplored, physical processes, their observations have been predominantly confined to the study of individual objects (as in the case of INTERNATIONAL ULTRAVIOLET EXPLORER and HST satellites) or relatively small fractions of the sky (as in the case of recent balloon- or shuttle-borne imagers). As a consequence, we still lack a modern, sensitive all-sky UV survey and our knowledge of the UV sky as a whole relies essentially on the pioneering mission of the satellite TD-1 in the early 1970s, whose survey was later published as a catalog.

In order to properly compare the capabilities of this UV facility with those of later space imagers, one should be familiar with the most common units used in UV astronomy. Typically the fluxes of UV sources are given in 'monochromatic magnitudes' m_λ defined as follows:

$$m_\lambda = -2.5\log(f_\lambda) - 21.175 \qquad (2)$$

where f_λ is the source flux density in erg cm^{-2} s^{-1} Å^{-1} at wavelength λ. As an alternative one can adopt the so called 'AB magnitudes' defined as:

$$\mathrm{AB} = -2.5\log(f_\nu) - 48.60 \qquad (3)$$

where flux units f_ν are now expressed in erg cm^{-2} s^{-1} Hz^{-1}. The latter system has been specially defined to coincide with V magnitudes for a source with a flat spectrum and its (wavelength dependent) conversion into monochromatic magnitudes becomes $m_{\mathrm{UV}} = \mathrm{AB} - 2.26$ in the middle of the UV domain (200 nm).

With reference to the above photometric scales, the TD-1 catalog content, including ~58 000 sources brighter than $m_{\mathrm{UV}} = 8.5$ measured in four UV spectral bands

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centered at ≈155, 195, 235 and 275 nm, appears comparable to that available to optical spectroscopy (i.e. the Henry Draper catalog) about a century ago, thus highlighting the persisting gap between UV and optical astronomy.

TD-1's successful flight showed the potential of long-lived, UV orbiting observatories, i.e. of UV-devoted telescopes operating on-board satellites. On the other hand, the advent of UV orbiters did not stop the development of other kinds of UV-oriented missions—both imagers and spectrometers—intended to exploit short-duration flights of rockets, stratospheric balloons and finally space shuttles. The first balloon-borne ultraviolet telescopes flown in the 1970s had the advantage of remarkably extending the observing time in comparison with sounding rockets, and though the observing window of these payloads floating at an altitude of ∼40 km is confined to the near-UV owing to atmospheric extinction, long-duration balloon flights are still felt appealing enough to conduct all-sky surveys. Just as an example, upgraded versions of the French–Swiss balloon-borne FOCA experiment, which surveyed ∼70 sky square degrees imaging hundreds of galaxies down to a limiting magnitude $m_{\mathrm{UV}} \sim 19$, will presumably fly in the near future. Analogously, modern rocket-borne instruments such as the Narrowband Ultraviolet Imaging Experiment for Wide-Field Surveys (NUVIEWS) launched in 1996 turn out to be competitive in order to map the mid-UV background at a resolution of a few arcminutes.

What is more, even short-duration missions can result highly productive when *multi-task* payloads are brought into space. This is the case of the two consecutive ASTRO-1, ASTRO-2 Shuttle missions which hosted three co-mounted ultraviolet instruments: a UV imager (UIT), a spectrometer capable of measuring UV fluxes down to the Lyman limit (the Hopkins Ultraviolet Telescope HUT), and the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE).

Turning back to the orbiting telescopes which pioneered the access to the UV sky, one should mention the rich dataset (consisting of pre-selected targets) of another successful mission, the Astronomical Netherlands Satellite (ANS) launched into a polar elliptical orbit in 1974 and operated until early 1976. Its 22 cm diameter telescope focussed UV light through a $2'.5 \times 2'.5$ aperture onto the focal plane of a spectrometer with fixed slits, thus sampling five, close UV spectral bands 15–20 nm wide starting from ∼150 nm.

A few additional experiments compensated for the lack of all-sky surveys by means of their large sky coverage. Among them one should mention the Far-Ultraviolet Experiment S201 which operated from the surface of the Moon during the Apollo 16 mission in 1972 assuring ultraviolet imagery of 10–20° diameter fields, down to a limiting monochromatic magnitude $m_{\mathrm{UV}} \sim 12$.

Two additional wide-field UV imaging facilities, namely the Wide-Field UV Camera (WF-UVCAM) and a first version of the Far-UV Space Telescope (FAUST), operated during the Spacelab 1 flight aboard the Space Shuttle in the early 1980s. The WF-UVCAM's survey covered a large fraction of the sky, mostly in the southern hemisphere, taking advantage of its ultra-wide field of view (66°), imaged with a resolution of 5′. FAUST was conversely designed to image a smaller field of view (∼8°) with a better angular resolution (1–2 arcmin). Unfortunately the experienced on-orbit high background affected both experiments, whose data were recorded on photographic emulsions, and the best WF-UVCAM images did not record objects fainter than $m_{\mathrm{UV}} = 9.3$, while almost no objects were detected by FAUST. A second opportunity for this telescope came at the time an improved version flew on board the Space Shuttle Atlantis in 1992. This time the telescope, taking advantage of a modern microchannel plate imaging detector, was capable of reaching a limiting magnitude $m_{\mathrm{UV}} = 13.5$ at 165 nm, as planned. Altogether FAUST's UV images covered a sky area of 0.33 sr (i.e. about 3% of the whole sky) thus assuring UV photometry of more than 4000 star-like and extended sources.

Among UV archive images currently being analyzed are the data obtained by UIT and those continuously being added to HST archives. UIT, namely a 38 cm telescope equipped with two selectable cameras providing both far- and near-UV images by inserting suitable filters, gave extremely useful overall pictures of a wide variety of UV *extended* sources such as supernova remnants, globular clusters, OB associations, spiral galaxies and circumnuclear starbursts. As far as the UV imaging capabilities of HST are concerned, one should take into account that its UV-sensitive instruments, though providing unmatched subarcsec resolution and limiting magnitudes, suffer either from poor long-wavelength rejection (WFPC2) or restricted field of view (FOC, STIS); in this respect the best use of HST as a UV imager are in snapshot surveys of the very central regions of galaxies and star clusters.

UV spectroscopy

As in any other field of observational astronomy, the amount of physical information carried by UV spectroscopy is far wider than simple photometry and/or imaging. This can explain the large effort devoted to bring into space UV spectrometers as early as possible in the history of space exploration, as well as the great scientific achievements of relatively simple facilities, like the IUE satellite.

UV spectrographs flown in the last few decades are characterized by improving performances in terms of limiting flux, sensitive spectral range and resolving power $R = \lambda/\Delta\lambda$ (a resolving power $R = 1000$ corresponds to the capability of recognizing individual features as close as a thousandth of their wavelength λ).

Among the early successful instruments one has to include a satellite of the OAO series, namely the OAO-3, named COPERNICUS, which was launched in 1972 and operated for eight years. Copernicus carried as the main ultraviolet experiment the UV Princeton equipment

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consisting of a 80 cm telescope and a grating spectrometer equipped with four UV-sensitive phototubes covering a short (95–145 nm) and a long (165–300 nm) wavelength range. The first high resolution UV spectra (down to $\Delta\lambda = 0.5$ nm) of early-type *bright* stars are due to this facility, though the primary goal of this mission was to make use of interstellar absorption lines, as seen against UV spectra of bright early-type stars, to estimate abundances in the interstellar medium.

The end of the same decade represented a turning point due to the launch of the International Ultraviolet Explorer (IUE). This long-lived, extremely successful satellite was brought into a geosynchronous elliptical orbit and operated as a guest observer facility from two stations located on either side of the Atlantic Ocean. Its instrumentation consisted of a 45 cm telescope with a 16′ field of view, equipped with two echelle spectrographs covering two overlapping ranges from 115 nm to 335 nm. The majority of spectra were obtained through a large, oval aperture $10'' \times 20''$ in size. The satellite could operate at low ($R \sim 300$) and high ($R \sim 10\,000$) resolution, providing a spatial resolution orthogonally to the dispersion of $\sim 4''$. Its archive, containing about 108 500 spectra, is a unique heritage the UV community will continue to exploit in the future.

A step forward in UV spectroscopy came with the two consecutive missions of the HUT telescope (see above) thanks to its unique capability of exploring the UV energy distribution down to the Lyman limit (91.2 nm) and thus deriving reliable temperature estimates for hot thermal sources (e.g. stellar populations including objects with $T_e \sim 20$–$30\,000$ K). More precisely, HUT consists of a 90 cm telescope with a spectrograph covering the 82.5–185 nm region in the first order coupled with a photon-counting microchannel-plate intensifier providing a resolution of $\Delta\lambda = 0.3$ nm. Besides 18″ and 30″ circular apertures for point source observations, rectangular apertures of $9.4'' \times 116''$ and $17'' \times 116''$ are available to obtain extended source spectra.

UV-sensitive spectrographs operated also on board HST since the beginning of its operational life. First-generation instruments were FOS and GHRS, both sensitive to UV wavelengths and largely complementary. The former UV/optical device operated at low and moderate resolution ($R \simeq 250$ and 1300) with a variety of apertures to optimize throughput, while two photon-counting detectors (digicons) could be used to select either a blue (115–550 nm) or a red (165–850 nm) channel. An interesting feature of FOS was its capability of isolating subarcsec regions of an extended source. Conversely, GHRS was a UV-dedicated instrument capable of obtaining much higher resolution spectra (up to $R \sim 80\,000$) of small wavelength intervals (from 28.5 nm to less than 1 nm). The above UV-sensitive spectrographs have been replaced in 1997 by STIS, an innovative instrument making use of two-dimensional detectors, thus providing *spatially resolved* long slit or slitless spectroscopy from 115 to 1100 nm from low to medium spectral resolution ($R \sim 600$–$14\,000$), together with high resolution UV echelle spectroscopy up to a resolving power $R \sim 100\,000$.

The extreme UV

Overcoming atmosphere opacity by means of space-borne telescopes is not enough when moving to the EUV portion of the spectrum. Actually, at wavelengths shortward of the Lyman limit (91.2 nm) observations are hampered by the intervening opacity of the interstellar medium (ISM), a phenomenon due to the absorption of line-of-sight atoms of hydrogen as well as of neutral and singly ionized helium (below 50.4 nm and 22.8 nm, respectively).

Moreover, as stressed above, a conventional optics consisting of curved reflecting mirrors would indeed absorb photons at wavelength shortward of ~50 nm and the goal of getting the majority of such radiation reflected can be achieved only by imposing on travelling EUV photons sufficiently low incidence angles. In other words, one has to resort to specifically designed telescopes, including a series of (metal) grazing-incidence surfaces, to focus EUV light.

Since the beginning of EUV astronomy interplanetary probes and manned spacecrafts played quite a large role in this field. This is the case, for instance, of the earliest measurements of the EUV background (i.e. below Lyα) obtained by means of simple Geiger counters on board Soviet probes Venera 5 and 6. A later major step in the exploration of the EUV sky was made possible in 1975 during the the joint Apollo–Soyuz mission. Its EUV experiment—a 37 cm grazing-incidence telescope with selectable fields of view of a few degrees—discovered the first four EUV point sources, thus showing that, counter to the prevailing opinion at that time, EUV astronomy was indeed possible. Other long-lasting experiments, namely modern UV spectrometers (UVS) employing microchannel plate intensifiers and covering the range 50–170 nm, were part of the scientific payload of VOYAGER 1 and 2 which started their journey into interplanetary space in 1977. A modified spare UV spectrometer (the EUVS experiment) built for the above Voyager mission has been finally adapted to the presently operating GALILEO spaceprobe, thus assuring EUV/UV spectral capabilities from 54 to 128 nm.

The modern age of EUV astronomy came at the beginning of our decade thanks to the all-sky survey performed by the EUV Wide Field Camera on board the x-Ray ROSAT satellite. Such a camera explored the whole sky in two, slightly overlapping bands (6–14 nm and 11–20 nm) and the resulting final catalogue contains 479 EUV sources, consisting mainly of hot white dwarfs and late-type (i.e. no hotter than the Sun), active stars.

An additional successful facility which, though brought into orbit in the Shuttle's payload bay, operated twice (in 1993 and 1996) as a free-flyer space UV/EUV telescope, was the German/US ORFEUS-SPAS platform. The ORFEUS instrument (Orbiting and Retrievable Far- and Extreme Ultraviolet Spectrometer) consists of a 1 m

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telescope equipped with two spectrographs, one of which, devoted to EUV, covered the region between 40 and 120 nm with a fairly high resolving power ($R = 3000$).

Actually, the present-day reference dataset for the knowledge of the EUV sky is represented by the source catalogs, images and the spectral atlas of the EXTREME ULTRAVIOLET EXPLORER (EUVE) satellite, launched in 1992. This NASA-funded facility includes three grazing-incidence, co-aligned telescopes and an EUV spectrometer/deep survey instrument. The first three scanning telescopes, which are perpendicular to the spacecraft spin axis and possess a 5° field of view, allowed a *complete* survey of the EUV sky to be made in four bandpasses from 7 to 76 nm, while the fourth telescope could simultaneously scan the sky over a $2^\circ \times 180^\circ$ area along the ecliptic (i.e. the plane of Earth's orbit). The latter telescope, aligned parallel to the spacecraft spin axis pointing away from the Sun, was allowed to integrate on a given source for a time as long as ~0.5 h during a single orbit (vs a typical 500 s exposure of the main survey), so as to provide much deeper images.

In some respect, one can state that with the advent of the EUVE satellite, whose spectrometers/deep survey instruments were later made available to specific investigations proposed by Guest Observers, the field of EUV astronomy gained its own identity, separate from other previously exploited, nearby spectral windows.

Achievements of UV astronomy

The overall sky picture

Though suffering from considerable limitations (mainly in terms of sky coverage) the above large effort devoted to UV astronomy gave us an overall view of the sky at these wavelengths. Owing to the opacity of the interstellar gas, the sky seen in the EUV passband is obviously quite 'foggy', as only nearby and/or the brightest sources can be detected. In particular, the number of detectable extragalactic objects, possibly obscured also by their own source opacity, becomes extremely low in the EUV, whereas the coronally active, *cool* stars dominate by far. Conversely, the regular UV sky, hosting both hot stars and faint UV-bright galaxies as well as the Milky Way starlight background scattered by interstellar dust, appears more populated and—in some respect—more familiar.

The solar system and the Sun

Among major efforts (and achievements) of UV astronomy in the solar system one should surely mention the study of comets and Jupiter's auroral activity. IUE observations of the comet IRAS–Araki–Alcock led, for instance, to the discovery of an unexpected molecule (S_2) never observed before in any astrophysical object, while a specific coordinated IUE/Galileo probe UV campaign at the end of the IUE operational lifetime was successfully devoted to characterize the timescales of global auroral phenomena.

Since UV and EUV solar spectroscopy are presented in detail elsewhere, suffice it to remember here the most recent successful solar mission SOHO (Solar and Heliospheric Observatory) which has given unprecedented insight on the nature of the solar corona and the generation of the solar wind by means of UV spectroscopy and visible light polarimetry.

The interstellar medium

For a long time it was well known that the space between stars is filled by highly rarefied gas and microscopic solid particles, generally referred as 'interstellar dust'. UV spectroscopy provided the tool to properly investigate the composition of interstellar gas by analyzing at sufficiently high resolution the resonance absorption features of common elements towards bright stars and indirectly gave information on the constituents of dust particles, showing, for instance, that the extinction they operate on the UV light shows a typical 'bump' around 220 nm.

Stars and star clusters

The impact of UV studies of stars (individual, binary or in clusters) is incalculably large, spanning an extremely wide variety of classes, evolutionary phases and phenomena.

Roughly speaking, one could identify a few major subfields, namely the study of hot (massive) stars, (active) cool stars, interacting binaries and old/young globular clusters.

The role of very massive (30–100 $M_\odot$) hot stars and their progeny (e.g. WOLF–RAYET STARS and LUMINOUS BLUE VARIABLES) can be fully appreciated taking into account that—when present—they dominate the appearance of their parent galaxies and, what is more, heavily affect their evolution through continuous mass loss, supernova explosions and ionizing radiation.

Observations in the UV domain are particularly well suited to characterize the physics of strong stellar winds produced by the above stars, as most of the strongest transitions of ionic species in their accelerated envelopes fall shortward of 200 nm. At the same time, at the opposite end of the star temperature scale, UV data are needed to investigate the nature of activity in chromospheres and coronas of stars as cool as $T_e \sim 3000$ K.

Moreover, interacting binary systems like SYMBIOTIC STARS—generally consisting of a cool red giant and a hot white dwarf—are prone to extensive UV investigations being characterized by highly energetic interaction processes such as colliding star winds and nova-like outbursts. In addition, specific phenomena such as the conversion of UV emission lines originated near the hot component into optical emission lines in the extended atmosphere of the cool giant (Raman scattering), can give clues to the geometric structure of the binary system.

When moving to the study of (old) galactic GLOBULAR CLUSTERS—large systems containing up to a million stars—one knows from optical observations that the large majority of their stellar population is quite cool, thus leaving as UV emitters only stars crossing specific hot evolutionary phases. Space-borne UV investigations confirm indeed these expectations, as highly evolved

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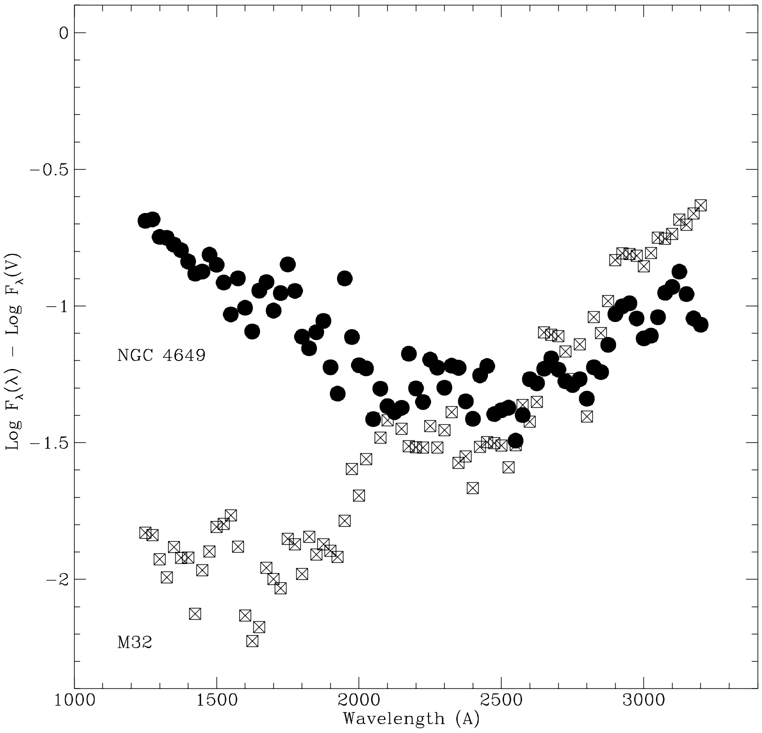

Figure 4. Comparison between the IUE energy distributions of NGC 4649, a typical metal-rich giant elliptical (filled circles) and the low-luminosity metal-poor elliptical M32 (crossed squares), normalized to the visual flux. The adopted flux scale is logarithmic. Note the striking difference of the two spectra in the UV region dominated by the hottest stars, as opposed to the approximate match longward of ~200 nm.

single hot stars often dominate the integrated UV light of the whole cluster and populated 'tails' of lower luminosity hot (up to $T_e \sim 20\,000$ K) helium-burning stars also emit most of their light in the UV domain. At the same time, the present capability of detecting much fainter UV sources provide a more complex and potentially interesting scenario where other classes (eruptive variables, the mysterious 'BLUE STRAGGLERS', etc) play a role. The above picture is at variance with what is seen in the *younger*, blue populous clusters of the LARGE MAGELLANIC CLOUD (LMC), where hot evolved stars are still lacking and young, hydrogen-burning massive stars emit most of the UV flux.

Supernova 1987A

The nearby supernova which appeared in the LMC in February 1987, monitored on a regular basis with all possible telescopes since the time of the explosion, is by far the best studied object of its class. It is specifically mentioned here because a substantial contribution to the knowledge of its nature and early evolution came from intensive UV spectroscopy assured by the IUE satellite and, since the time of its launch in 1990, by HST. In particular the STIS spectrograph on-board HST recently provided the first visual and ultraviolet *spatially resolved* (~0.″1) spectra of the exploded star. Among the exciting results obtained by means of UV observations one has to include the identification of the SN progenitor which unexpectedly turned out to be a *blue* supergiant star, the possibility of deriving the complex structure of the intervening medium both in our own galaxy and in the LMC toward the UV-bright supernova, and an accurate determination of the distance to the supernova (51.4 ± 1.2 kpc).

Galaxies

When observing external galaxies at ultraviolet wavelengths one can expect to reveal their hot stellar content as well as possible highly energetic phenomena (including transient events) in their central regions. The latter is obviously the case of galaxies hosting Active Galactic Nuclei (AGN). These two classes of UV sources reflect, in turn, two distinct mechanisms (thermal/non-thermal) of radiation emission.

Stellar populations in galaxies

The study of hot stellar populations by means of spaceborne, UV-sensitive facilities turned out to be among the most intriguing and fruitful in the recent past.

For *disk-dominated* galaxies UV imagery offers a direct way of recognizing active sites of star formation at different scales (spiral arms, nuclear rings, star-forming complexes, etc) as well as of estimating the *amount* of newly formed stars. Moreover, the pattern of star-forming sites seen in

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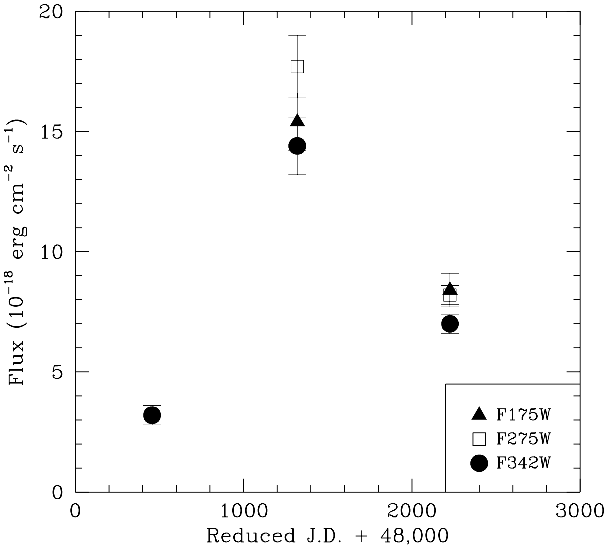

Figure 5. The light curve of the flaring UV-bright central spike of NGC 4552 in three close UV HST/FOC passbands. Epochs are July 1991, November 1993 and May 1996, respectively. The source has brightened by a factor ~4.5 between 1991 and 1993, and has decreased its luminosity by a factor ~2.0 between 1993 and 1996 (from Cappellari *et al* 1999 *Astrophys. J.* **519** 117).

the UV for nearby galaxies of different morphologies can be of great relevance (once these objects are adopted as templates) to reconstruct the morphological class of very distant galaxies whose visible and IR images recorded by ground-based telescopes will actually show—owing to cosmic expansion—their rest-frame UV emission.

The role of UV observations becomes even higher when a galaxy hosts a 'starburst', i.e. a major event of star formation dominating its energetic output (see STARBURST GALAXIES). For these objects, the capability of addressing many key issues, such as the starburst morphology and duration, the nature of the so-called super star clusters as well as the impact of dust obscuration is largely dependent on the availability of UV data, indeed.

In addition, UV still represents the most promising 'window' one can exploit in order to understand the *late* evolution of older stars belonging to *spheroidal* systems, such as elliptical galaxies and spiral bulges. In this respect, a very informative feature one can investigate *exclusively* in UV is the rise of the spectrum of giant ellipticals shortward of ~200 nm (alternately dubbed 'UV rising branch', 'UV-upturn' and UVX), due to the presence of hot components in the stellar populations of these galaxies (figure 4).

Though the first hint of this phenomenon came from the pioneering observations of the ANDROMEDA GALAXY bulge by means of the OAO-2 satellite, a much deeper insight into the origin of this behavior has been reached only by means of the large body of data recorded by IUE. Actually, IUE spectra showed that the relative amplitude of the hot UV-bright component varies from one galaxy to another and especially that—among present-day evolved stellar populations—the phenomenon depends on the chemical composition, as the higher the mean metallicity (percentage of elements heavier than hydrogen and helium) of the galaxy, the higher its UV flux. A further strict constraint for any acceptable model about the origin of the UV upturn, namely its narrow range in temperature ($T_e \sim$ 20–24 000 K), came later from the spectra down to the Lyman limit obtained by means of HUT.

Since then astronomers face the need of identifying one (or more) evolved stellar components sufficiently hot, bright and long-lived as to provide the observed UV flux, while simultaneously matching the correlation between UV excess and metal content. Such a debate is still going on and will presumably not come to an end until new, higher-quality space-based data (able to provide direct constraints on abundances in the atmospheres of the stars that produce the UV flux) will be available. Once this puzzle is solved one can expect to add to this investigation a more evolutionary perspective, i.e. to constrain both age and metallicity of distant ellipticals by 'catching' the onset of the UV upturn at a specific epoch in the past.

AGN-related phenomena

The major effort in the study of AGNs in the UV consisted of prolonged (generally multiwavelength) spectral monitoring campaigns aiming at deriving their continuum and emission-line variability characteristics. The IUE-based campaigns focussed on the behavior of SEYFERT 1 GALAXIES highlighting many common features, such as the time delay shown by broad emission lines in response to UV continuum variations.

Moreover, a major advantage when *imaging* AGNs against their cool-star-dominated surroundings in the UV is the capability of hugely enhancing their contrast in comparison with optical and IR images, taking advantage of their non-thermal flat spectrum. In this way searches for very low-luminosity, nuclear UV-bright sources and their possible AGN-like activity become feasible.

An outstanding example of such a UV-facilitated, serendipitous discovery is the protracted UV flare of an unresolved spike at the center of the optically normal elliptical NGC 4552 which turns out to be, on the basis of its ionized gas luminosity, the faintest known AGN. The evolution of such a phenomenon, loosely sampled in the UV by means of HST from 1991 to 1996 (see figure 5), has presumably to be ascribed to the tidal stripping of a star in a close fly-by with a central supermassive compact object.

Forthcoming UV missions

Among survey-devoted projects, the largest scientific yield is expected from the Galaxy Evolution Explorer (GALEX), a NASA Small Explorer (SMEX) mission approved in 1997. GALEX is intended to obtain a series of spectroscopic and imaging surveys in the range 130–300 nm in order to study both the UV properties of local galaxies and the star formation and metal production history of galaxies over the redshift [1] range $0 < z < 2$. Mission plans include two imaging surveys with a resolution of 3″, namely an all-sky survey down to the limiting magnitude of AB = 21.7 (at 200 nm) and a subsequent deep imaging survey over a 200 square degree field expected to reach a limiting magnitude of AB = 26 in two contiguous UV ranges (135–180 nm and 180–300 nm). Such a dataset will then be complemented by three objective-prism spectroscopic surveys, again in the bandpass 135–300 nm with a spectral resolution of 15 nm.

As far as HST UV imaging is concerned, one should remember that in the servicing mission scheduled for Spring 2000 the FOC will be replaced by the Advanced Camera for Survey (ACS), a third-generation imager 7× more sensitive than WFPC2 in the near-UV and equipped with a 1024 × 1024 pixel CCD (21 μm pixel size) assuring also an improved sampling of the image.

A breakthrough in far-UV spectroscopy is instead expected by the launch of the FAR-ULTRAVIOLET SPECTROSCOPIC EXPLORER (FUSE). This innovative satellite, specifically designed to get unparalleled high-resolution spectra ($R \sim$ 24 000–30 000) in the range between the Lyman α and Lyman limit (90.5–119.5 nm) consists of four co-aligned 39 × 35 cm mirror telescopes coupled with four spherical, holographically ruled gratings. Two MCP detectors are used, while a set of science apertures (from 1.25″ × 20″ to 30″ × 30″) are available. Its main scientific goals will be to measure the deuterium abundance in a variety of astrophysical objects and derive the distribution of hot and/or cold gas in the interstellar and intergalactic medium as well as to address many astrophysical problems such as the nature of hot layers of stellar atmospheres.

The last HST servicing mission of 2002 will include, in turn, the installation of the Cosmic Origin Spectrograph (COS), an instrument which, taking advantage of its single-reflection design, will assure a throughput an order of magnitude higher than the present-day STIS spectrograph.

The future

A major exploratory UV facility like GALEX, assuring a survey down to monochromatic magnitudes $m_{\mathrm{UV}} = 19$–20, will surely boost the interest for follow-up UV studies at the beginning of the next millennium. On the other side, the expected rise of observing demand will clash with the very limited access to the UV domain available to the general astronomical community (essentially confined to the overscheduled HST and FUSE, whose observing time will be mainly devoted to a few key projects). Moreover, following the priorities assigned by specifically appointed committees, the Next Generation Space Telescope (NGST), expected to be operational in the 21st century, will be optimized for near-IR imaging and spectroscopy and not for UV.

In this framework it will be mandatory to take as much advantage as possible of piggy-back UV instruments on major high-energy astrophysics missions (such as the UV/optical monitor on-board the XMM satellite, for instance), as well as to explore complementary cheap alternatives such as telescopes mounted on long-duration, high-altitude balloons able to survey the whole sky around 200 nm.

In the long run, a very promising approach could be also the emerging World Space Observatory (WSO) concept, i.e. a series of space observatories devoted to different wavelengths domains and, analogously to IUE and other facilities, made available to the world-wide astronomical community to attack major problems in astrophysics and cosmology.

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[1] Owing to the expansion of the universe the light coming from distant galaxies shows a redshift (expressed as $z = \Delta\lambda/\lambda$ in terms of increased wavelength), thus appearing redder and redder with increasing receding galaxy velocity which, in turn, reflects increasing distance and lookback time. As a consequence, a given redshift range Δz corresponds to a well defined interval in lookback time, once a specific cosmological model is chosen.

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