Chapter XI:
Future instrumentation and facilities

https://doi.org/10.1017/S1743921322003416 Published online by Cambridge University Press

https://doi.org/10.1017/S1743921322003416 Published online by Cambridge University Press

Massive Stars Near and Far
Proceedings IAU Symposium No. 361, 2024
J. Mackey, J. S. Vink, & N. St-Louis, eds.
doi:10.1017/S1743921322003416

Ultraviolet observations of massive stars and the instrumentation to come

Ana I. Gómez de Castro[1,2]

[1]Joint Center for Ultraviolet Astronomy, Universidad Complutense de Madrid, Avda. Puerta de Hierro s/n, 28040 Madrid
email: aig@ucm.es

[2]S.D. Física de la Tierra y Astrofísica, Fac. CC Matemáticas, Plaza de Ciencias 3, 28040 Madrid

Abstract. The wealth of information obtained about massive stars from observations at ultraviolet (UV) wavelengths has been fundamental to understand their structure and the mechanisms regulating their evolution. There are however, important aspects that have not yet been addressed due to the lack of data and the relevant instrumentation such as the role of binarity and magnetic fields or the impact of low metallicity in the evolution of massive stars. There are plans to develop UV spectropolarimeters, UV monitors and very efficient telescopes with high collecting surfaces that will revolutionize the field. In this contribution, a short update on the current and foreseen UV instrumentation is provided.

Keywords. Massive stars, ultraviolet observations, ultraviolet instrumentation.

---

1. Introduction

The peak of the spectral energy distribution of the OBA stars is at ultraviolet (UV) wavelengths thus, massive stars have been the preferred targets and the most extensively observed sources since the very beginning of UV astronomy. Early UV telescopes such as the Carruther's lunar telescope (Carruthers & Page 1972) or the Copernicus (OAO-3, Rogerson et al. 1973) observatory had massive stars among their favourite targets and opened a fundamental window to study radiatively driven winds (Abbott 1978) as well as to evaluate their impact in the evolution of the interstellar medium (ISM).

The full understanding of the physics involved in the acceleration of the winds came later, with the systematic, high dispersion spectroscopic observations obtained with the International Ultraviolet Explorer (IUE, Boggess et al. 1978), the Hubble Space Telescope (HST, www.stsci.edu/hst) and the Far UV Spectroscopic Explorer (FUSE, Moos et al. 2000). Main results were the complete spectral characterization of massive stars, the understanding of line-driven winds, the determination of the relevance of the metallicity in the wind properties and terminal velocity, or the detection of clumps in the wind. The main diagnostic tools used for these works were the P-Cygni profiles produced by the resonance transitions of CIV, NV, OVI and the lines of the iron group which cover a broad range of ionization stages and enable the determination of the metallicity and other stellar properties such as the effective temperature (Najarro et al. 2006 and references therein). Later on, the GALaxy Evolution eXplorer (GALEX, Martin et al. 2005) mapped the extended star forming disks of spiral galaxies (Thilker et al. 2007) and provided a unique view of massive star formation triggering and the role of large scale galactic stresses on it. HST's high sensitivity allowed the study of massive stars in nearby galaxies and a deeper understanding of the role of metallicity in OBA stars physics and evolution (see i.e.

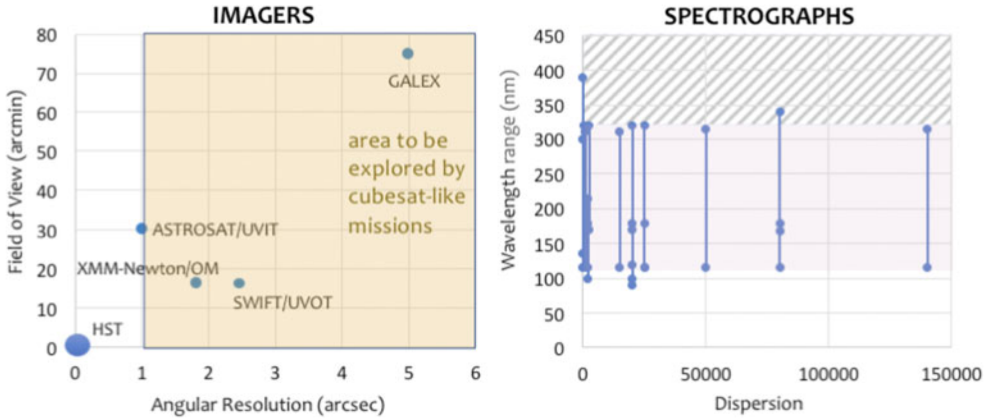

Figure 1. Main characteristics of the UV instrumentation already flown. *Left)* Imagers: the wide field of view and small angular resolution area, suitable to be explored for cubesat-like missions in the future is shadowed in yellow. *Right)* Spectrographs

Garcia et al. 2017, 2019). The impact of UV observations in massive star studies is well addressed in this volume, including interacting binaries and cataclysmic variables (see, also the publications of the network of ultraviolet astronomy, nuva.eu/nuva-publications). These studies are also fundamental to understand the star formation history of the Universe and characterize starbursts in galaxies.

The space missions being defined in the 2020's, seek raising this knowledge through the development of large space telescopes, such as the Large UV Optical Infrared Surveyor (LUVOIR, `asd.gsfc.nasa.gov/luvoir/`) or the European UV Visible Observatory (Gómez de Castro et al. 2022a). There is also, a significant on-going effort to carry out spectropolarimetric measurements to measure OBA stars magnetic fields and to investigate the circumstellar environment. In this contribution, I will describe the current status of UV facilities and the plans being outlined for future missions.

2. Characteristics of the UV instrumentation already flown

The properties of the UV instrumentation already flown are summarized in Figure 1. Very few imaging instruments have been developed and two of them are small telescopes flown together with high energy missions such as UVOT in SWIFT or OM in XMM-Newton to detect the UV counterparts to high energy sources. Both SWIFT and XMM-Newton have a field of view ≤ 20 arcmin and an angular resolutions of ~ 2". There has always been an UV imager on board HST, providing very high angular resolution and a broad range of UV filters (see Figure 1 in Gómez de Castro et al. 2022a). On the contrary, GALEX has provided a very wide field of view and low angular resolution.

All the imagers to date have been flown into Low Earth Orbit (LEO) and thus, observations at some specific wavelengths are hampered by the Earth geocoronal emission. As shown in Figure 2, the geocoronal emission is especially strong in the Lyman-α (Lyα) transition of Hydrogen and in several Oxygen transitions (resonance transition of OI at 130.4 nm, semiforbidden trransition of OI] at 135.6 nm and forbidden transition of [OII] at 247.1 nm). To avoid the impact of the airglow, some of the UV surveyors, such as GALEX, have avoided imaging the UV sky below 135 nm.

The effect of geocoronal emission can be removed in spectroscopic observations and, as shown in Figure 1, flown spectrographs have operated in the full UV range (from 90 to 350 nm). All sorts of dispersions have been utilized; from the very low dispersions achieved with prisms (*e.g.* the prism PR110L in the ACS instrument on board HST

https://doi.org/10.1017/S1743921322003416 Published online by Cambridge University Press

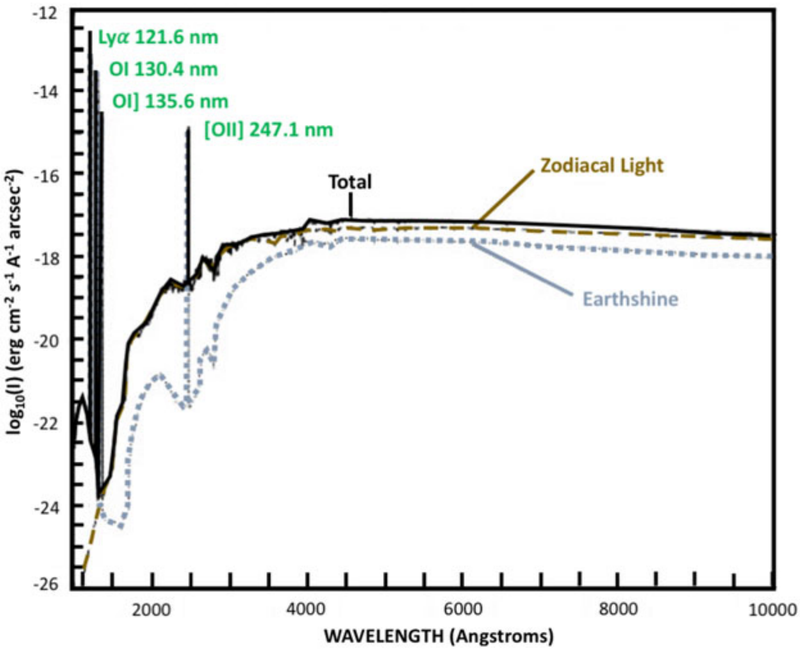

Figure 2. Sky background intensity. The zodiacal contribution corresponds to $m_V = 22.1$ arcsec^{-2}. The earthshine is for a target which is 38^o from the limb of the sunlit Earth. The geocoronal airglow line intensities are plotted at "average" intensities (`hst-docs.stsci.edu/stisihb/chapter-6-exposure-time-calculations/6-5-detector-and-sky-backgrounds`).

provides dispersions as low as 80 at 150 nm) to the very high dispersion provided by the HST/STIS, echelle mode (Kimble et al. 1998).

Unfortunately, the only information available on UV spectropolarimetry was achieved with the Faint Objects Spectrograph on HST that was decommissioned early in the project to allocate the COSTAR. Also, efficient mid-dispersion (R∼ 20,000 - 30,000) spectrographs with simultaneous coverage of the 115 nm - 315 nm range have not been flown yet.

3. UV missions planning

In recent years, many proposals to build and operate UV telescopes have been submitted to the space agencies world-wide. Adding to the scientific interest of this range, is the perception that the end of the 32 years old HST mission is nearing. A summary-sketch with the space missions and the proposals being discussed at this time is outlined in Figure 3. The main characteristics of the missions to be flown in the coming 5 years are summarized in Table 1. Looking further ahead in the future, there are many projects and plans; they go from dedicated spectropolarimetric missions (PolStars, Arago, URIEL) to UV surveyors (CASTOR, INSIST, MESSIER) and a plethora of small, proposals (many cubesat like) designed as technology demonstrators (CASSTOR) or devoted to single-science cases (ESCAPE), see Gómez de Castro et al. 2021 for a description of these projects. All this activity is also fundamental to develop the scientific and technological knowledge that will pave the way to future, very ambitious missions such as LUVOIR, a 10-m class UV-optical-infrared telescope, or the European Ultraviolet-Visible Observatory (EUVO).

Among the coming missions, Spektr-UF/WSO-UV stands out by its versatility and its scientific program open to the world-wide community.

https://doi.org/10.1017/S1743921322003416 Published online by Cambridge University Press

Table 1. List of approved missions (excluding those already flying in June 2022).

Project Name	Main operator	Main characteristics	Status
Xuntian	CNSA	UV-optical surveyor with FoV=1.1^ox1.1^o and Ang. Res.= 0.15?. NUV filter covers the 255nm-320nm range. Diameter of the primary: 200 cm Orbit: LEO	Launch end 2022
SPARCS	NASA	Dedicated cubesat mission or exoplanetary research. Imaging with filters in the 115nm-320nm spectral range. Diameter of the primary: 9 cm Orbit: LEO/Sun synchronous	Launch end 2023
Spektr-UF/WSO-UV	ROSCOSMOS	UV observatory operating in the with instrumentation for imaging and spectroscopy. Diameter of the primary: 170 cm Orbit: HEO/Geosynchronous	Launch 2025/26
ULTRASAT	ISA	Wide field (204 deg^2) UV transients monitor operating in the 230nm-290 nm range. Diameter of the primary: 33 cm Orbit: HEO/Geosynchronous	Launch 2025/26

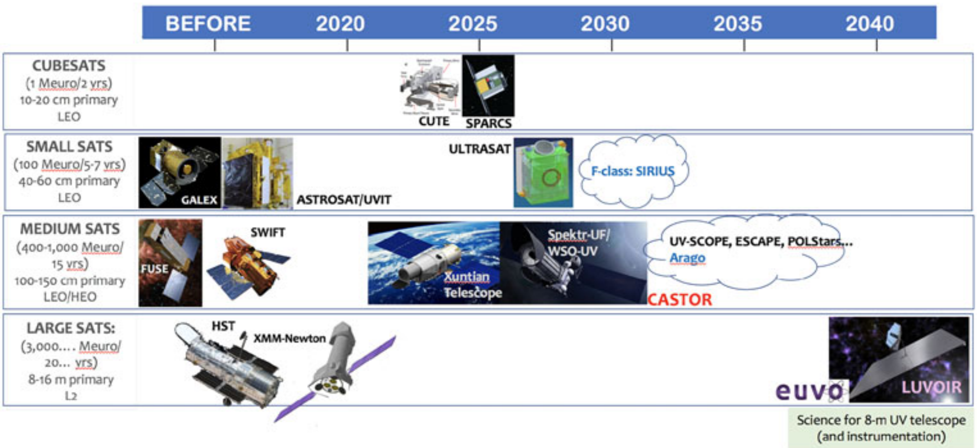

Figure 3. UV missions: on-going, programmed and proposed. The list is not exhaustive, especially at the low mass end.

3.1. *Spektr-UF/WSO-UV*

The World Space Observatory - Ultraviolet mission (Spektr-UF/WSO-UV) is a multipurpose space observatory to study the Universe in the 115 nm - 310 nm range using high- and low- resolution spectroscopy, high sensitivity imaging and slitless spectroscopy (Shustov et al. 2022). The project is included in the Russian Federal Space Program 2016-2025; it is the third mission of the Spektr series to be flown after Spektr-R (2011-2019) and Spektr-RG (launched in 2019, in operation). WSO-UV will operate from a geosynchronous orbit allowing for long (up to 10 h), uninterrupted observations and enjoying a dark UV sky. The scientific operation of WSO-UV is managed through three fundamental programs: the core program, the guaranteed time to the funding bodies of the project and the international program. With the launch coming near 2025, the calls for the various programs will be issued in upcoming years.

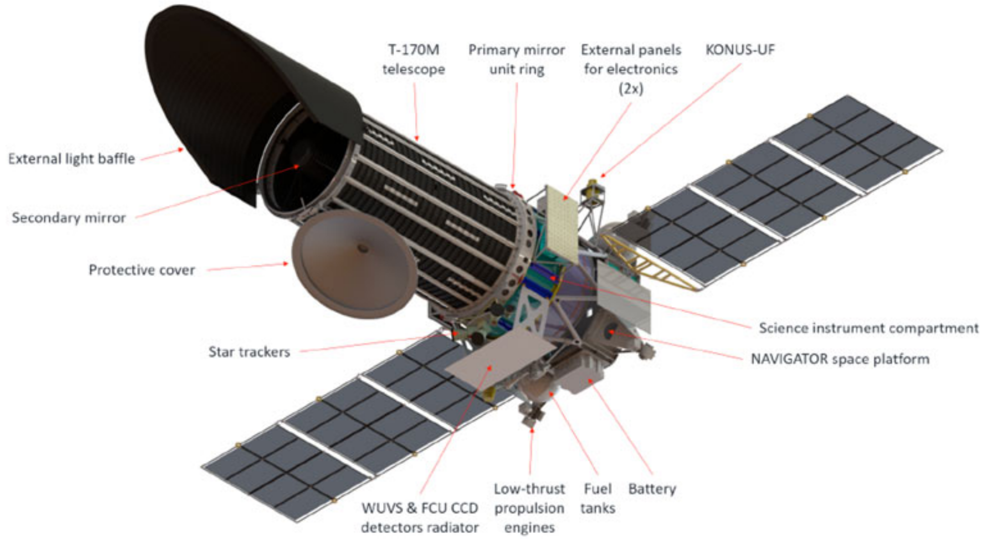

Figure 4. Spektr-UF/WSO-UV spacecraft.

The WSO-UV scientific payload includes the T-170M telescope, a 170 cm aperture telescope with a Ritchey-Chretien mounting, and the instrumentation: WUVS (WSO-UV Spectrograph), FCU (Field Camera Unit) and UVSPEX (see Fig. 4).

The WUVS includes three channels:
• VUVES channel providing high resolution (R $\sim$ 50,000) echelle spectra in the 115-176 nm spectral range.
• UVES channel providing high resolution (R $\sim$ 50,000) echelle spectra in the 174-305 nm spectral range.
• LSS (long-slit spectrograph) channel providing low resolution (R $\sim$ 1,000) spectra in the 115-310 nm spectral range.
Each of the three WUVS channels has an almost identical custom detector consisting of a custom CCD272-64 inside a vacuum enclosure. The main challenges of the WUVS detectors are to achieve high quantum efficiency in the FUV-NUV range, to provide low readout noise (≤ 3 e^- at 50 kHz) and low dark current (≤ 12 e^-/pixel/hour), to operate with integral exposures of up to 10 hours and provide good photometric accuracy. Teledyne e2v designed three variants of a custom CCD272-64 sensor with different UV AR coatings, optimized for each WUVS channel. WUVS is being developed under the responsability of the Institute of Astronomy of the Russian Academy of Sciences (INASAN).

The FCU consists of two channels:
• The Far UV channel: provides an angular resolution of 0.1 arcsec over a field of view of 2× arcmin^2. The channel is equipped with an MCP detector using CsI as photosensitive substrate, *i.e.*, the detector is solar blind and sensitive to the 115 nm - 176nm spectral range. The channel is equipped with a set of step filters (similar to those available in the SBC channel of the HST/ACS instrument) for spectral band selection and, two prisms to carry out slit-less spectroscopy. PR122 has been designed to provide resolution, R$\sim$ 600, in Lyα and R$\sim$ 500, in the nearby OI resonance transition (130.4 nm) to detect transiting hot Jupiters and super-Earths. PR155 provides a resolution, R$\sim$ 600, in the

https://doi.org/10.1017/S1743921322003416 Published online by Cambridge University Press

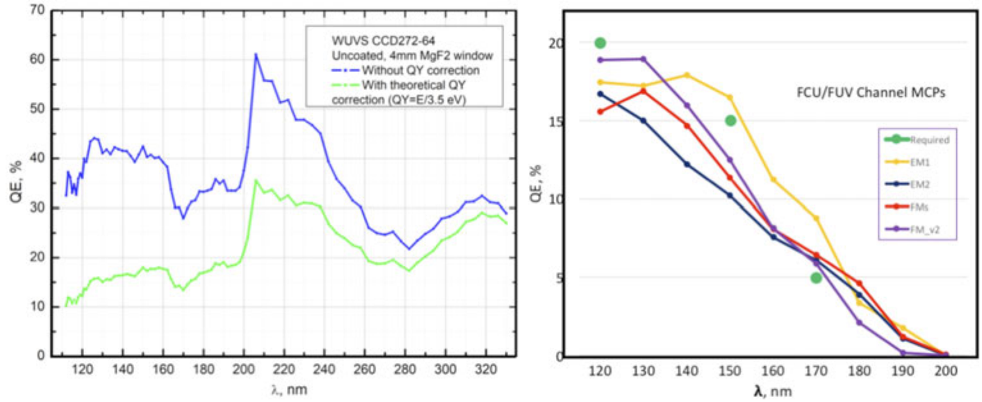

Figure 5. Quantum efficiencies of the detectors (engineering models, and also MCP flight models) used in the FCU instrument on board Spektr-UF/WSO-UV.

CIV resonance transition (155 nm) to measure terminal velocities of massive stars in nearby galaxies.

• Near UV channel: provides an angular resolution of 0.15 arcmin over a field of view of 7.5× arcmin^2. The detector is a Teledyne e2v CCD and the target spectral coverage is 174-305 nm. The CCD sensitivity goes up to 1000 nm thus, the channel is equipped with filters for UV, but also optical observations.

The quantum efficiency of the detectors measured in the engineering and flight models is shown in Figure 5. The FCU is a joint instrument developed by INASAN in collaboration with the Universidad Complutense de Madrid (UCM).

In 2020-2021, an additional instrument UVSPEX was incorporated to the project. UVSPEX is a UV spectrograph optimized to detect Oxygen in the exosphere of Earth-like exoplanets. UVSPEX will operate only in the 115-135 nm range with a spectral resolution of $\sim$ 10,000 to resolve the OI blend at 130.4 nm. UVSPEX is being developed by the Rikkyo University (Tokyo) and the Space Research Institute of the Russian Academy of Sciences (IKI).

Official, updated information on the project status, instrumentation and scientific calls can be found on the servers of the project (www.inasan.ru/en/sw/wso-uv/ and jcuva.ucm.es).

4. Seeking for a common framework for UV photometry

The advent of widely spread cubesat technology during the next decade is going to change space astronomy. Instead of a few large missions, many small missions dedicated to specific scientific purposes, surveys and time-domain astrophysics will be flown. It is in the best interest of the scientific community to define some basic standards to enable easy data comparison and test the reproducibility of the observations. The International Astronomical Union (IAU) recommends the implementation of some well defined bands which are summarized in Figure 6 and Table 2.

The main considerations for the selection of the bands in the system have been: a smooth integration of the dataset already available, such as the GALEX survey, a good coverage of the spectral range that avoids the Lyα geocoronal emission (since most of the cubesats will fly in low Earth orbits which is the most affected by geocoronal emission) and, to enable the study of the UV bump at 225 nm in the extinction curve. The UV bump is produced by small carbonaceous particles and depends on the line of sight.

https://doi.org/10.1017/S1743921322003416 Published online by Cambridge University Press

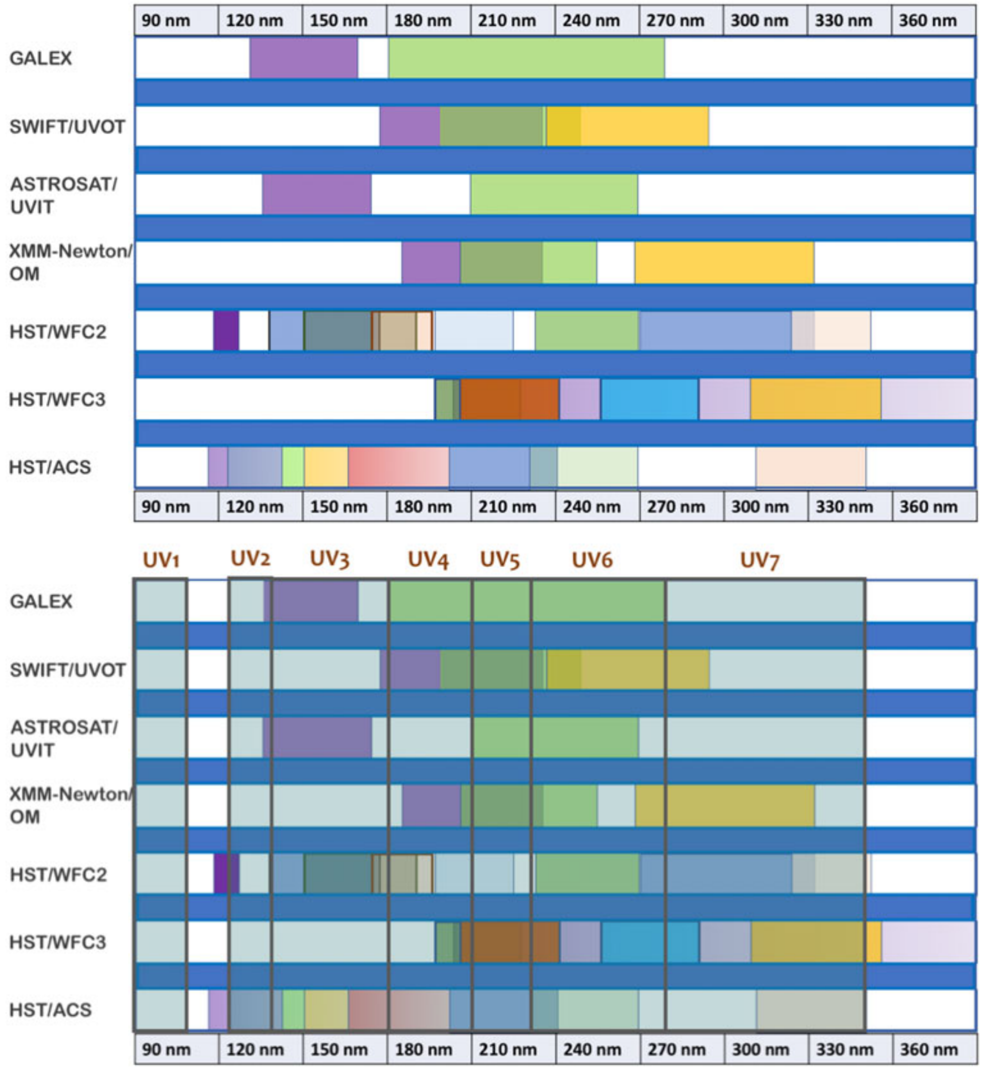

Figure 6. *Top:* Sketch outlining the spectral coverage of the UV filters (or bands) used for imaging purposes in astronomy (GALEX, HST/ACS, HST/STIS, XMM-Newton/OM, SWIFT/UVOT) from Gómez de Castro et al. 2022b. Note that the final transmittance also depends on the response of the detector. This is particularly relevant for the MCP type detectors often used in UV Astronomy since, they use photocathodes only sensitive to specific spectral ranges. We refer the reader to the Instruments manuals and handbooks for more details on the filters (precise transmittance curves, effective wavelengths, etc.). Note that, for instance, several ACS filters are step filters that cannot be adequately represented in this plot. Also, filters are many and overlap high in the HST instruments. *Bottom:* the windows of the recommended IAU filters (see Table 2), over-plotted on the filters sketch (grey boxes).

5. Summary

There are fundamental aspects of astrophysics requiring a deep understanding of massive stars, the relevance of binarity in their evolution and the role that magnetic fields and metallicity play in it. For this purpose, new instrumentation is required to measure magnetic fields (spectropolarimetric instruments) and study massive stars in low metallicity environments (*i.e.* increasing the effective area of the space telescopes).

https://doi.org/10.1017/S1743921322003416 Published online by Cambridge University Press

Table 2. UV photometric bands proposed as standards.

Band ID.	Spectral range	Target	Implementation
UV1	90-110 nm		
UV2	125-140 nm		
UV3	140-180 nm	GALEX FUV	GALEX
UV4	180-210 nm	Continuum shortward of the UV bump	
UV5	210-230 nm	UV bump	
UV6	230-280 nm	Near UV continuum, Fe bands	F250W (ACS/HRC)
UV7	280-350 nm	Ozone cut-off window	F330W (ACS/HRC)

During the coming years, the lead in UV astronomy will move to eastern countries; the next 2-m size missions are the Xuntian telescope and the Spektr-UF/WSO-UV observatory. Xuntian will be launched in 2022-23 and operated by the Chinese Space Agency mainly, as an all-sky surveyor. Spektr-UF/WSO-UV will be set in orbit a few years later (2025-26) and will be operated by the Russian Space Agency as a space observatory open to the world-wide community with periodic announcements of opportunity.

Proposals for UV observatories have not been selected neither by NASA, nor by ESA during the last two decades. At the time of writing this summary, both agencies are evaluating proposals for mid-size missions which have been submitted to the announcements of opportunity issued in 2021. On the table, for study, there are several UV missions such as Arago in the ESA system and ESCAPE, UV SCOPE or PolStars in the NASA system. In case any of them is selected, it will fly in the mid 30's thus, far in the future. The Canadian Space Agency has selected a UV-optical mission, a wide-field surveyor, to be implemented in the coming 15 years; the consortium to run the project will be set in the next few years.

In the meantime, many small missions, including some cubesat like, are being designed and promoted: CUTE, SPARCS, ULTRASAT are just some few examples. It is expected that this number grows significantly in the coming years due to the rapidly growing opportunities to fly small satellites into space. The IAU is concerned about data curation and sharing in this context. For this reason, it recommends that those satellites running spectroscopic observations post-process the data into standard photometric bands (see Fig. 6) to feed a basic database that can be shared by the world-wide community. It also advises that missions running photometric surveys try to implement bands as close as possible to those defined in Figure 6 or transform their photometry into these bands.

Acknowledgements

This work has been funded by the Spanish Ministry of Research and Innovation through grant PID2020-116726RB-I00.

References

Abbott, D.C., 1978, *ApJ*, 225, 893

Boggess, A., Carr, F. A., Evans, D. C., et al. 1978, *Nature*, 275, 372

Carruthers, G. R., Page, T. 1972, *Science*, 177, 788

Garcia M., Herrero, A., Najarro, F., et al. 2017, *Proc IAU Symp*, 329, 313

Garcia M. Herrero A., Najarro F., Camacho I., et al. 2019, *MNRAS*, 484. 422

Gómez de Castro, A.I., Barstow, M.A., Brosch, N., et al. 2021, *UV Astronomy and the quest for the origin of life*, Elsevier, ISBN:978-0-12-819170-5

Gómez de Castro, A.I., Barstow, M.A., Brosch, N., et al. 2022a, *ExpA*, 44G, DOI: 10.1007/s10686-022-09854-9

Gómez de Castro, A.I., Brosch, N., Bettoni, D. et al. 2022a, *ExpA*, submitted

Kimble, R.A., Woodgate, B.W., Bowers, C.W., et al., 1978, *ApJ*, 492, L83

Martin, D. C., Fanson, J., Schiminovich, D., et al. 2005, *ApJ*, 619, L1

Moos, H. W., Cash, W. C., Cowie, L. L., et al. 2000, *ApJ*, 538, L1
Najarro, F., Herrero, A., Verdugo, E., 2006, *ApSS*, 303, 153
Rogerson, J. B., Spitzer, L., Drake, J. F., et al. 1973, *ApJ*, 181, L97
Shustov, B., Gómez de Castro, A.I., Sachkov, M., 2022, *Proc. of the SPIE*, 12181-104
Thilker, D. A., Bianchi, L Meurer, G Gil de Paz, A Boissier, S. et al. 2007, *ApJS*, 173, 538

https://doi.org/10.1017/S1743921322003416 Published online by Cambridge University Press