PROCEEDINGS OF SCIENCE

The driving science for the WSO-UV mission

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UV-astronomy is a very demanded branch of space astronomy. Many dozens of short-term UV-experiments in space as well as long-term observatories in last decades have brought fundamental data for the understanding of the physics and chemistry of the Universe. Unfortunately no large UV observatories are planned by the major space agencies to be launched in the coming 10 – 15 years, unless the ROSCOSMOS led WSO-UV mission. In this article, we briefly describe the current status of the field and the role to be played by the WSO-UV. WSO-UV was described in previous publications in many details, that is why only a basic information and current state of the project are briefly presented in this paper. A brief overview of major science topics that have been included in the Core Program of the WSO-UV is presented. Attention is focused on the most recent research in these directions. We conclude that the Core Program of the WSO-UV will open new frontiers is astrophysical research in fields as demanding as exoplanetary research or the chemical evolution of the Universe.

Keywords: UV-astronomy - space projects - ultraviolet: general

XI Multifrequency Behaviour of High Energy Cosmic Sources Workshop
25-30 May 2015
Palermo, Italy

PoS(MULTIF15)071

1. Introduction

During almost half a century astronomers have enjoyed continuous access to the 100–300 nm far- and near- ultraviolet (FUV and NUV) spectral ranges where the resonance transitions of the most abundant atoms and ions (at temperatures between 3 000 and 300 000 K) reside. This UV range is not accessible from ground-based facilities. Many dozens of short-term UV-experiments in space as well as long-term space observatories have brought very important knowledge on physics and chemistry of the Universe. Let's briefly remind major achievements of UV-astronomy in the past century:

- Direct detection of H_2 molecules with "Aerobee-150" (Carruthers, 1970).
- Discovery of the hot phase of the interstellar medium with "Copernicus" (Jenkins and Meloy, 1974).
- Measuring of D/H with "Copernicus" (Rogerson and York, 1973).
- Massive accurate determination of the chemical composition of stars with IUE (1978–1996).
- Detailed studies of stellar mass loss phenomena across the H-R diagram with IUE.
- Identification of Warm-Hot Intergalactic Medium as the reservoir of missing baryons with HST, FUSE.
- Giant progress in understanding physics and chemistry of planetary atmospheres with HST.
- Discovery of star formation progressing in the extended galactic haloes with GALEX.

In recent years new ideas and concepts of UV-observatories and instruments were proposed in various countries. We briefly overview some of these new projects.

Brosch et al. (2014) described concepts for small space telescopes that are able to provide significant UV science and can be realized with small (but realistic) budgets ($\sim$ 10 MEuro). The concepts are based on nano-satellites (cubesat technology) carrying small optics, with no redundancy, without producing intermediate models prior to flight model, and using COTS (custom off-the-shelf) components. One of the proposed targets is to survey regions near bright sources that were not achievable by GALEX because of detectors limitations. The authors described either a concept of deployable optics that could provide large collecting areas and high angular resolution while packaged in the small volume of a nano-satellite.

Next year we expect launch of UIT — Ultraviolet Imaging Telescopes on the ISRO Astrosat observatory (Hutchings et al. 2014). Major UV-instruments are two 40 cm telescopes for FUV and NUV ranges, with FOV of 0.5 degrees and resolution $\sim$ 1 arcsec.

At the conference "Challenges in UV astronomy" (see Gómez de Castro et al. 2014b) D.Valls-Gabaud on behalf of MESSIER Consortium has presented a proposal of S/M-class satellite (to the French Space Agency (CNES)) for uncovering the unobserved low surface brightness universe. The mission concept includes a high quality UV camera with 45 cm mirror, $f/2.5$. The three mirrors off-axis design ensures a stable point spread function with very low wings. The focal plane includes a matrix of eight 4K$\times$4K CCDs, with plate scale $\sim$1 arcsec/pixel that will be used as a

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wide field detector. Other essential technical details include the use of a drift scan mode (TDI); very high ($< 0.05\%$) flat-fielding; 6 optical + two UV filters (ugrizW IB200 NB200). The cost of the project is estimated to be at the level of 150 MEuro.

The low surface brightness ultraviolet universe is the science target for ISTOS (Imaging Spectroscopic Telescope for Origins Surveys) either. The project is a Small Explorer mission (50 cm telescope) designed to detect and map the emission from the cosmic Intergalactic Medium (Martin, 2014).

Côté (2014) presented an updated version of the CASTOR project. CASTOR (the Cosmological Advanced Survey Telescope for Optical and UV Research) was proposed to the Canadian Space Agency (CSA) and it would carry out deep, high-resolution imaging at ultraviolet and blue-optical wavelengths. Operating close to the diffraction limit, the 1 m CASTOR telescope would have a spatial resolution comparable to that of the Hubble Space Telescope (HST), but with an instantaneous field of view of $1.2^{\circ} \times 0.6^{\circ}$ – about two hundred times larger than that of the Advanced Camera for Surveys on HST. Imaging would be carried out simultaneously in three non-overlapping bandpasses: UV ($0.15 - 0.3\,\mu$), u ($0.3 - 0.4\,\mu$) and g ($0.4 - 0.55\,\mu$). In the blue-optical region, CASTOR imaging would far exceed that from LSST in terms of depth and angular resolution, even after a decade of LSST operations.

Neiner et al. (2014) described the project UVMag - a medium size space mission with a 1.3 m telescope equipped with a UV+optical spectropolarimeter. Adding polarimetric power to the spectrograph will multiply tenfold the capabilities of extracting information on stellar magnetospheres, winds, disks, and magnetic fields. Examples of the science objectives that can be reached with UVMag are presented for pre-main sequence, main sequence and evolved stars. UVMag is currently undergoing a Research and Technology study and will be proposed at the forthcoming ESA call for M-size missions under the name ARAGO.

Heap et al. (2014) proposed a space mission concept called Galaxy Evolution Spectroscopic Explorer (GESE) aimed at making a large ultraviolet spectroscopic survey of galaxies at redshift, $z \sim 1$ (look-back time of $\sim$8 billion years). GESE is a 1.5 m three mirror anastigmatic space telescope (f/5) with an NUV multi-object slit spectrograph covering the spectral range, 0.2– 0.4 μ (0.1–0.2 μ as emitted by galaxies at a redshift, $z \sim 1$) at a spectral resolution of $\Delta\lambda = 0.6$ nm.

Scowen et al.(2013) presented the project HORUS (High-ORbit Ultraviolet-visible Satellite). This is a 2.4-meter class space telescope that will conduct a comprehensive and systematic study of the astrophysical processes and environments relevant for the births and life cycles of stars and their planetary systems, to investigate and understand the range of environments, feedback mechanisms, and other factors that most affect the outcome of the star and planet formation process. This program relies on focused capabilities: near-ultraviolet (UV)/visible (200–1100 nm) diffraction-limited imaging; and high-sensitivity, high-resolution FUV (100–320 nm) spectroscopy. HORUS is expected to provide 100 times greater imaging efficiency and combines the resolution of STIS with the throughput of COS.

All these projects lie in reasonable "cost-time" domain that makes their implementation feasible in a not too distant future. Unfortunately no large UV observatories are planned by major space agencies for launch in coming 10–15 years. As it concerns to longer term prospects a number of very ambitious projects of large aperture (4–16 m) space UV-optical telescopes is proposed. Most intensively discussed are: EUVO (European Ultraviolet & Visible Observatory), see Gómez de Castro (2014a); THEIA (Telescope for Habitable Exoplanets and Intergalactic/Galactic Astronomy), see Spergel (2010); ATLAST (Advanced Technology Large-Aperture Space Telescope), see Pasquale et al. (2010). The Cosmic Origins Program Analysis Group (COPAG) within NASA has recently released the Report[1] regarding large mission concepts to study for the 2020 US decadal survey that includes a flagship mission offering high spatial resolution, high sensitivity, and access to the full range of wavelengths covered by HST (91.2 nm âĂŞ 2 μm) to advancing key Cosmic Origins science goals in the 2020s and 2030s. The report includes an explicit mention to the need to improve the sensitivity at ultraviolet wavelengths between 91.2 and 110 nm .

In the next section, we present the project World Space Observatory – Ultraviolet (WSO–UV) which is well developed (C-phase of implementation) and seems to be the only 2-m class UV telescope for the next decade. WSO-UV will guarantee access to UV wavelength domain with capabilities similar to the HST.

2. WSO–UV mission

The World Space Observatory–Ultraviolet (WSO–UV) is a multi-purpose international space mission born as a response to the growing up demand for UV facilities by the astronomical community. The project is led by the Federal Space Agency (Roscosmos, Russia). In the Federal Space Program, which is a major planning document for space activity in Russia, the project has two names (aliases): "Spektr-UF" and WSO-UV. The "Spektr" series of the Russian Space Program includes either "Spektr–R" ("Radioastron") and "Spektr-RG" missions. WSO-UV was described in previous publications in many details (see Shustov et al. 2009, 2011, 2014; Sachkov et al. 2014a, 2014b), for this reason only basic information and current state of the project are briefly presented here.

The WSO–UV consists of a 1.7 m aperture Ritchey-Chrétien telescope with a focal length of 17 m. The telescope provides an accessible field of view of 30 arcmin on the telescope focal surface. The telescope is equipped with instrumentation designed to carry out high resolution spectroscopy, long-slit low resolution spectroscopy and direct sky imaging. The WSO–UV Ground Segment (GS) is under development by Spain and Russia and both countries will coordinate the Mission and Scientific operations and will provide the satellite tracking stations for the project. The nominal lifetime is 5 years with a planned extension to 10 years.

The telescope T-170M passed dynamic and thermal tests. Optics of the telescope is being manufactured. Both optical quality and quality of coatings (Al+MgF_2) meet technical requirements. In Fig. 1 the preparation of primary mirror of the T-170M is illustrated.

Major science instruments are: the WSO–UV spectrographs (WUVS) and Imaging and Slitless Spectroscopy Instrument (ISSIS).

WUVS is under the responsibility of Russia. It consists of three channels (Panchuk et al.2014):

- The far UV high resolution spectrograph (VUVES) that will permit to carry out echellé spectroscopy with high resolution ($R \sim 50000$) in the 115–176 nm range.

- The near UV high resolution spectrograph (UVES) to carry out echellé spectroscopy with $R \sim 50000$ in the 174–310 nm range.

[1] http://cor.gsfc.nasa.gov/doc/COPAG_Flagship_Response_final.pdf

Figure 1: In Coating of primary mirror of the T-170M telescope.

- The Long Slit Spectrograph (LSS) that will provide low resolution ($R \sim 1000$), long slit spectroscopy in the 115–305 nm range. The spatial resolution will be better than 0.5 arcsec (0.1 arcsec as the best value).

All spectrographs will be equipped with a CCDs e2V cooled down to $-100°$C (Shugarov et al. 2014).

The spectral resolution provided by VUVES and UVES channels is similar to that offered by STIS (HST) at medium resolution with its echellé gratings, but higher than the maximum resolution provided by COS (HST) ($R \sim$20 000). To estimate the effective area of WUVS we used *measured values* of all the relevant elements of optical path, i.e. reflectivity of optical surfaces, transmittance of MgF2 windows used to protect CCDs of WUVS, efficiencies of echellé and cross-dispersion gratings and quantum yield of CCD e2V. These are presented in Fig. 2. The estimated effective areas of WUVS channels in comparison with COS/HST and STIS/HST are presented in Fig. 3.

The imaging functions of the WSO–UV are assigned to the Imaging and Slitless Spectroscopy Instrument (ISSIS) that permits to carry out imaging and slitless spectroscopy in the 115–320 nm spectral range. The instrument is to be equipped with two MCP detectors, with CsI and CsTe photocathods for FUV and NUV observations, respectively. The resolution in the slitless spectroscopy mode is about 500. Capabilities of the ISSIS are expected to be similar to those of Advanced Camera for Survey (HST). ISSIS is under responsibility of Spain (Gómez de Castro et al. 2014c).

WSO–UV will use the Russian NAVIGATOR platform which was designed in Lavochkin Science & Technology Association (Russia). The platform was successfully in-flight tested by the âĂIJRadioastron" mission (launched in 2011) and some commercial satellites. WSO–UV is planned for a launch from Baikonur (Kazakhstan) with a Proton rocket.

The brief outline of the current state of the Project may consist of few phrases. Funding in Russia is guaranteed. There are not critical technical problems in the implementation of the project. International cooperation is well established. Some organizational problems (induced by known sanctions against Russia and problems with funding in Spain) moved the launch date to the

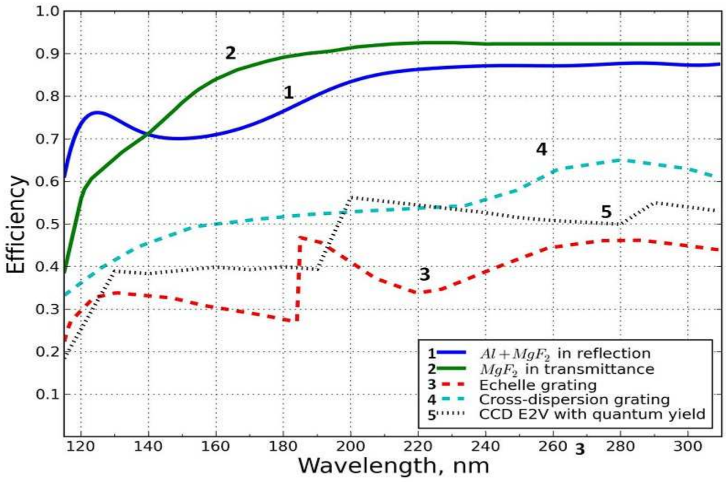

Figure 2: Measured reflectivity of optical surfaces (1), transmittance of MgF2 windows used to protect CCDs of WUVS (2), efficiencies of echellé (3) and cross-dispersion (4) gratings and quantum yield of CCD e2V (5).

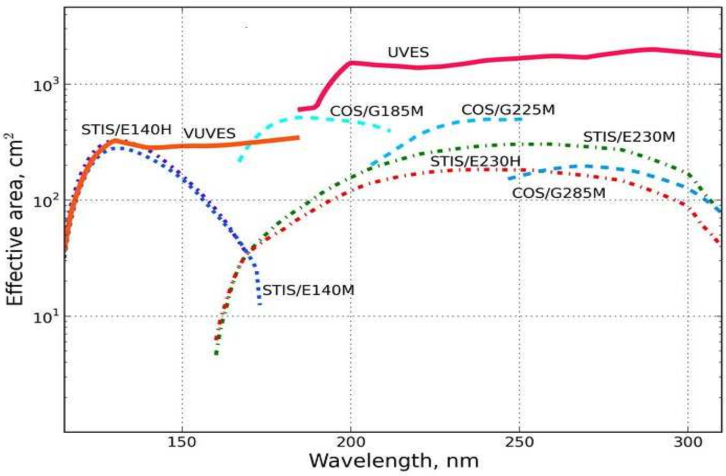

Figure 3: Comparison of the expected effective area of the WSO–UV Spectrographs, UVES and VUVES, and HST/COS and HST/STIS.

end of this decade.

3. WSO–UV Key Science Issues

For any space observatory, it is important to focus the science program on the most challenging problems that can be treated efficiently with such an instrument. Typically these problems constitute the core program of the project. The Core Program of the WSO–UV was thoroughly discussed in past years (see e.g. Gómez de Castro et al., 2009; Shustov et al , 2011). The Program includes:

- The determination of the diffuse baryonic content in the Universe and its chemical evolution. The main topics will be the investigation of baryonic content in warm and hot Inter Galactic Matter, of damped Lyman-α systems.
- The study of the formation and evolution of the Milky Way.
- The physics of accretion and outflows: stars, black holes, and all those objects dominated by accretion mechanisms. The efficiency and time scales of the phenomena will be studied, together with the role of the radiation pressure and the disk instabilities.
- The investigation of the extrasolar planetary atmospheres and astrochemistry in presence of strong UV radiation fields.

Over time, the urgency of any problem changes, so one needs to keep track of the development of this area of science and to confirm previous priorities or change them. So we focus attention on some of the most recent research in the research directions included in the Core Program.

3.1 The baryonic content of the IGM

As it is noted by Nicastro (2014) baryons are missing at all astronomical scales in the Universe, from galaxies to the large scales of structure formation and the Universe as a whole. Independent of the different models for the evolution of the Universe the major baryonic component of the Universe must be associated with the intergalactic medium (IGM). Hydro-dynamical simulations for the formation of structures, tend to re-concile the different "missing-baryon" problems and predict that most of the baryonic matter of the Universe is hiding in a hot and tenuous gaseous phase (Warm-Hot Intergalactic Medium, or WHIM). The WHIM at temperatures $T = 10^5 - 10^7$K, most likely accounts for a $\sim 40-50\%$ of the baryons to the cosmological mass density in the local Universe. Other large ($\sim 20-30\%$) part of baryons is in the form of highly photoionized intergalactic hydrogen and helium (see e.g. the cosmological simulations by Cen & Ostriker 2006). Nicastro (2014) suggests observations of X-ray emission to efficiently reveal the baryons hidden in WHIM. We think that these observations are useful but far from to be exhaustive. Paradoxically the highest share ($\sim 40\%$) of missing baryons is referred to the local Universe ($z \leq 2$). For more distant Universe the problem on missing baryons is not so keen. This is because of the fact that distant objects, emitting/absorbing in UV, are unobserved from the Earth but can be observed in optical range due to cosmological shift. Lack of UV observations prevents the revealing missing baryons in local Universe. We think that that UV emiting/absorbing plasma (WHIM and Lyα-absorbers) is a major reservoir of missing baryons. Broad HI-Lyα absorption is one of the most promising techniques to map the distribution of the WHIM.

3.2 The baryons in DM halo and formation of galaxies.

Models of the formation of galaxies like our Milky Way have predicted that the central galaxy contains only a modest fraction of the available baryons (Klypin et al. 2011). Galaxies are inefficient producers that have converted a small portion of their available gas into stars. Over the past years it has become increasingly apparent that galaxies also exhibit a diffuse baryonic component within the dark matter halo that extends far from the inner regions to the virial radius and beyond. This gas is a target of COS-Halos Project (HST). Werk et al. (2014) analyzed the physical conditions of the cool, photoionized ($T \sim 10^4$K) circumgalactic medium (CGM) using the COS-Halos suite of gas column density measurements for 44 gaseous halos within 160 kpc galaxies at $z \sim 0.2$. WSO-UV is believed to be an efficient instrument to contribute to the inventory of baryons in galactic vicinity.

3.3 Astronomical engines

Astronomical engines (stars, black holes, etc...) can accelerate large masses to velocities close to the speed of light or generate sudden ejections of mass as observed in Supernova explosions. WSO-UV will provide key inputs to answer the basic open questions concerning physics of these objects. Some few examples are:

1. High resolution UV spectroscopy will allow to determine the structure of the accretion flow on magnetic cataclismic variables and on T Tauri stars and to measure the physical conditions and clumpyness of the outflows. It will also allow to study the source of energy that powers the extended dense ($\geq 10^{10}$cm^{-3}) and hot (T$_e \geq 60,000$ K) envelopes that have been detected around T Tauri stars (GĂŹomez de Castro & Marcos-Arenal 2012). The luminosities of these envelopes are about 0.2 L$_\odot$.

2. Low resolution spectroscopy will allow to measure the general physical conditions and metalicities of the Broad Lines Emission Region in Active Galactic Nuclei. Reverberation mapping will allow to study the kinematics and the mass of the central supermassive black holes. Also the atmospheres of the hot accretion disks in cataclysmic variable stars will be studied and the role of disk instabilities in triggering the outbursts.

3. The high sensitivity FUV camera will allow to detect jets through their Ly-α and to resolve the thermal structure of the jets and the regions shocked by them. It will also allow to survey star forming regions to detect planetary-mass objects in regions like σ-Orionis and to study the magnetic activity and accretion processes in these free-floating planetary-like objects which are at the low mass end of the molecular clouds fragmentation scales.

3.4 Extrasolar planetary atmospheres

The Instrumentation of the WSO–UV project is very important and helpful for exoplanet studies and the characterization of the exoplanet-stellar environment. However, there are several difficulties that are at the origin of the major uncertainties on any estimations of exoplanetary atmosphere properties (Fossati et al. 2014):

- the relative faintness of the UV stellar emissions;

- the variability of the sources;

- signal contamination by both the sky background signal (at some spectral lines) and the instrument response.

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While the first difficulty can be resolved by focusing on a few close-by and UV-bright stars, the signal variability from both the source and the instrument is a real problem that should be addressed to build a reliable diagnostic to extract an accurate description of the upper atmosphere and of the interaction region between the exoplanet and the impinging wind from its host star.

It should also be mentioned that WSO–UV can be used not only for standard exoplanet observations and characterizations but also for observations of biomarkers. Biomarkers like ozone have very strong transitions in the ultraviolet. These are electronic molecular transitions, hence several orders of magnitude stronger than the vibrational or rotational transitions observed in the infrared or radio range. The spectral resolving power required to detect biomarkers in the atmosphere of exoplanets is not a crucial capability. A resolution of $R \sim 10000$ is adequate to these investigations, and even $R \leq 1000$ could be enough to detect the broad band signatures of many molecules. The presence of biomarkers and other constituents in the atmospheres can be searched by WSO-UV high resolution spectrographs for about 100 exoplanets orbiting K, G and F-type main sequence stars.

4. Concluding remarks

World Space Observatory – Ultraviolet (WSO–UV) will be the only 2-m class UV telescope with capabilities similar to the HST for the next decade. WSOï£¡UV will work as a space targeted observatory with a core program, an open program for scientific projects from the world-wide community and national (funding bodies) programs for the project partners (see Malkov et al. 2011). Core Program of the WSO-UV remains very relevant. Current information on the WSO–UV project can be found at the official web site: http://wso-uv.org.

Acknowledgements: Ana I. Gómez de Castro acknowledges support from the Ministry of Economy and Competitiveness of Spain through grant AYA2011-29754-c03-01.

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