ON THE FUTURE OF ULTRAVIOLET (UV) ASTRONOMY

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Abstract: The situation of UV astronomy: current facilities, future projects and the great science to be done is briefly outlined.

1 Introduction

The UV range supplies a richness of experimental data which is unmatched by any other domain for the study of hot plasma with temperatures in between 10^4 K and 10^5 K; the high excitation lines and the resonance lines of the most abundant species in the Universe are observed in UV. Plasma at these temperatures is observed in all astrophysical environments extending over hot stars, cool stars and planetary atmospheres, gaseous nebulae, the warm and hot components of the ISM, circumstellar material, the close environment of black holes of all masses from X-Ray Binaries to Nuclei of Galaxies, accretion disks, and the intergalactic medium. In addition, the electronic transitions of the most abundant molecules, such as H_2, are observed in this range which is also the most sensitive to the presence of large molecules such as the PAHs. In this brief contribution, the situation of UV astronomy is outlined.

2 The UV facilities

There are three major astronomical facilities working in the UV range: the *Hubble Space Telescope* (HST), the *Galaxy Evolution Explorer* (GALEX) and *Far Ultraviolet Spectroscopic Explorer* (FUSE). HST and FUSE are observatory missions while GALEX is mainly devoted to carry out the first all-sky UV survey. Let us summarize the main characteristics of the UV instrumentation in these missions (see also Table 1 for a summary).

2.1 HST (1990-...)
(URL:www.stsci.edu/hst)

HST is a 2.4 m telescope which was deployed in low-Earth orbit on 1990; it is a cooperative project of ESA and NASA. HST is a general purpose telescope with a core program: the accurate determination of the Hubble constant, through the observations of Cepheid variable stars in the galaxies of the Local Group.

The first generation instruments with UV capabilities were the *High Speed Photometer*, the *Goddard High Resolution Spectrograph* and the *Faint Object Spectrograph*. Currently, the *The Wide Field and Planetary Camera 2* (WFPC2), the *Advanced Camera for Surveys* (ACS) and the *Space Telescope Imaging Spectrograph* (STIS) provide access to the UV range both for imaging and spectroscopic work. The WFPC2 is a 2-dimensional imaging photometer which covers the spectral range between approximately 115 nm and 1050 nm. It simultaneously images a 150"x150" "L"-shaped region with a spatial sample of 0.1 arcsec per sample and a smaller 34"x34" square field with 0.046 arcsec per pixel. There are 8 UV filters with central wavelength between 130 nm and 333 nm. However, the presence of significant red leaks in the UV filters, together with the much greater sensitivity and wavelength coverage in the red part of the spectrum for CCD's, makes calibration of the UV observations difficult. As a consequence, the prime instruments for UV astronomers are the ACS and the STIS.

The ACS

The **ACS** is a third generation HST instrument and includes two channels suitable for UV imaging:

- a High Resolution Channel (HRC), with a field of view of 26"x29" covering the range from 200 to 1100 nm and a plate-scale of 0.027 arcsec/pixel. There are three broad band (FWHM $\simeq$ 400 Å) UV filters available centered at 220 nm, 250 nm and 330 nm.

- a Solar Blind Channel (SBC), with a field of view of 31"x35", spanning the range from 115 to 170 nm and a plate-scale of 0.032 arcsec/pixel.

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There is also a low resolution (grism) spectroscopic mode available with R$\sim$ 100.

The STIS

STIS is the prime ultraviolet instrument on-board the HST. It can be used for imaging, high-spatial resolution long-slit spectroscopy and high spectral resolution (echelle) spectroscopy.

- High resolution, long-slit spectroscopy is available in the 115-310 nm with low and medium spectral resolutions (∼1000 and ∼15,000, respectively). Slits of 52" length and widths between 0."05 and 2" are available.

- High spectral resolution echelle spectroscopy is available in the 115-315 nm range with resolutions $\sim 50,000$ and $\sim 114,000$.

- When STIS is used in imaging mode in the UV, the field of view is 25"x25" and the plate scale 0.0246 arcsec per pixel. Few filters are available: three narrow band filters with FWHM between 7 nm and 8.5 nm, centered in the Lα (121.6 nm), the CIII] (190.9 nm) and the MgII (280 nm) lines, plus some continuum filters with FWHM = 35 nm, centered at 270 nm and 182 nm, and two passband filters.

The wider field of view, the higher sensitivity and the greater selection of filters makes of the ACS the preferred instrument for UV imaging. However, STIS provides higher S/N than the SBC in the far UV and has some narrow band filters which are not available for the ACS.

2.2 FUSE (1999-...) (URL:fuse.pha.jhu.edu)

FUSE is a NASA-CNES-CSA supported astronomy mission that was launched on June 24, 1999, to explore the Universe using the technique of high-resolution spectroscopy in the far-ultraviolet spectral region. The Johns Hopkins University has the lead role in the mission, in collaboration with the University of Colorado at Boulder and the University of California at Berkeley.

FUSE obtains spectra from about 90.5 nm to 118.7 nm. The true resolution has been difficult to assess on-orbit (see URL: fuse.pha.jhu.edu/support/guide/). The spectral resolving power has been estimated to be $R = 20,000 \pm 2000$, and is nearly flat across the entire bandpass.

FUSE was designed with two primary objectives in mind: to study the physics of the hot component of the Interstellar Medium (ISM) and to estimate how much deuterium has been destroyed since the Big Bang.

2.3 GALEX (2003-2005)

(URL: www.srl.caltech.edu/galextech/)

GALEX is a 50 cm telescope, e.g. a small explorer class mission that is part of NASA's Structure and Evolution of the Universe theme. GALEX will perform both imaging and low resolution spectroscopy, conducting several types of surveys. GALEX will complement the capabilities of space observatories like HST (GALEX has a wide field of view), and the UV spectroscopic capabilities of FUSE, both currently in orbit.

GALEX is the first mission to conduct an all-sky survey in the ultraviolet with a significant sensitivity. Two imaging surveys in a far UV band (135-180 nm) and in a near UV band (180-300 nm) with 3"-5" spatial resolution will be carried out to 20-21 mag (AB). In addition, a spectroscopic survey in the 135 nm-300 nm band, with spectral resolution ~ 100 will be done over 100 square degrees. Detailed information about all GALEX surveys may be found in the GALEX web page (see above).

The scientific objective of GALEX is to characterize the UV properties of the galaxies to study their star formation history over the redshift range $0 < z < 2$.

3 The next generation of UV astronomy

There are two main facilities under study and/or development at this moment: the *International Virtual Observatory* (IVO) and the *World Space Observatory - Ultraviolet* (WSO/UV). In addition to these a limited sky survey specifically oriented to interstellar absorption (TAUVEX) will be launched in 2005 under a collaboration between ISA and ISRO.

3.1 The IVO

(URL:www.ivoa.net)

There are many projects on-going world-wide to create the so-called *Virtual Observatories*, which basically are computational tools that allow consulting, retrieving and processing the information stored in the Astronomical Archives (data from ground-based or space-based observatories, catalogues, etc...) for a given scientific purpose. The IVO alliance tries to coordinate this joint effort world-wide since it is necessary to define common standards for the scientific content of the data (astrometric, photometric, spectrophotometric, polarimetric standards) and for the data format. In addition, communication technologies ought to be common to all the archives to guarantee the required interoperability; a *rigourous* definition of the data is instrumental for the meaningful *scientific* operation of the IVO.

The largest archive of UV data is the Multimission Archive at the Space Telescope (MAST). It provides access to the HST, FUSE and GALEX archives as well as to the

Facility (lifetime)	Type of Instrument	Spectral Range (nm)	Field of view (arcsec)	Spectral Resolution R	Spatial Resolution
HST (1990-...)	Im-ACS(HRC)	200-1100	26x29	Broad band filters (FWHM $\sim$ 40nm)	0."027 pix^{-1}
	Im-ACS(SBC)	115-170	31x35		0."032 pix^{-1}
	Im-STIS	115-$\sim$350	25x25	Lyα, CIII], MgII Continuum filters	0."0246 pix^{-1}
	Sp-ACS	115-390	Grism	100	
	Sp-STIS	115-310	Long-Slit (52")	$\sim$15000 $\sim$1000	0."03 pix^{-1}
		115-315	(echelle)	140000 $\sim$50000	
FUSE (1999-...)	Sp	90.5-118.7		20000$\pm$2000	
GALEX (2003-2005)	Im	135-300	All-sky	Two broad bands: NUV(180-300) and FUV(135-180)	3"-5"
	Sp	135-300	(grism)	100	

Table 1: The main UV facilities working in 2003. Im: Imaging; Sp: Spectroscopy

first UV missions: Copernicus and the International Ultraviolet Explorer (IUE). Also, the data from many small missions are included (see Table 2). The MAST provides some tools for cross consultation of all the UV archives. Also cross-consultation with the ROSAT (X-ray) archive and some on-line catalogues is implemented.

IVO will allow the cross-consultation of the UV archives with the rest of the archives spanning the whole spectral range. It will also provide tools to produce directly scientific results as the Spectral Energy Distributions (SED), spectral line identifications and flux determinations or variability studies.

3.2 The WSO/UV

(URL:wso.vilspa.esa.es)

The WSO/UV is a 1.7 m telescope mainly designed to be a spectroscopy mission devoted to high resolution (echelle) spectroscopy (R=50,000) in the 110-340 nm spec-

Mission	Type of Observations	Number of Observations	Spectral Range (nm)	Main Characteristics
IUE	Sp	>10,4000	120-335	Aprox. 10,000 sources
Copernicus	Sp		90-156 & 165-315	551 sources, mostly bright stars
EUVE	Sp		7-76	300 sources, mostly Galactic
HUT	Spphot	491	91.2-185	Aprox 300 sources.
UIT	Im	1579	120-330	259 sources
WUPPE	Sp&Pol	467	140-330	169 sources
BEFS/ORPHEUS	Sp		90-190	75 objects
IMAPS/ORPHEUS	Sp	600	95-115	10 hot stars
TUES/ORPHEUS	Sp	239	90-140	62 targets

Table 2: UV data in the MAST archive (from URL:archive.stsci.edu). Sp: Spectroscopy; Spphot: Spectrophotometry; Im: Imaging; Pol: Polarimetry

tral range. It will also include optical and UV imaging capabilities (see Table 3); long-slit spectroscopic capabilities are under study. The optical design of WSO/UV is optimized to guarantee a maximum light throughoutput (a high effective area) so, although WSO/UV is slightly smaller than HST, it will be an order of magnitude more sensitive than HST/STIS (at R=50,000). Another important feature for the science to be carried out with WSO/UV is the orbit; it will be placed in the Lagrangian point L2 allowing spectroscopic monitoring which is heavily demanded by the astronomical community and difficult to carry out with the HST due to its low Earth orbit. The mission will have a core program focussed in two key problems for modern astrophysics: the formation of stars and planetary systems and the cosmological and chemical evolution of the intestellar and intergalactic medium up to $z \simeq 2$.

The World Space Observatory Project represents a new space mission concept, since it has grown out directly of the needs of a world wide distributed Astronomical community which demands access to the UV range after the HST era. Basic scientific requirements are improved sensitivity for high spectroscopy and hours-to-days monitoring capabilities. WSO/UV will allow to make full profit of the legacy of the previous UV missions and, especially of the GALEX, first all-sky UV survey.

As WSO/UV has been driven by the needs of scientists from many different countries, a new implementation model was needed to bring the World Space Observatory

Instrument and Type	Spectral Range (nm)	Field of view (arcsec)	Spectral Resolution R	Spatial Resolution
HRI Im	115-310	60	Narrow Band Filters Lyα,CIV,CIII,MgII (and few more to detemine)	0."03 pix^{-1}
HSI Im	115-310	300	Broad Band Filters for surveys (to determine)	0."15
OI Im	360-800	240	(to determine)	0."12
HIRDES Sp	102.8-310.0		50,000	

Table 3: The main characteristics of WSO/UV. Im: Imaging; Sp: Spectroscopy

to reality. The developments needed to make the anticipated launch of WSO/UV possible in 2008 are led by an open international committee of scientists the World Space Observatory Implementation Committee (WIC).

4 A science case for the future

The richness of the UV range is instrumental for the study of all the astronomical plasmas from few thousands to several hundreth thousand *Kelvin*. As it is not realistic to attempt to cover all the possible astrophysics in this brief contribution, we shall focuss on two key problems: the physics of the formation of stars and planetary systems, and the cosmological and chemical evolution of the intergalactic medium up to $z \simeq 2$, as an example.

4.1 The physics of the formation of stars and planetary systems

The formation of stars is an accretion process; the gravitational energy of the infalling material is stored in accretion disks which transforms it into radiation, thermal energy and mass ejection (winds). The Magneto-Rotational Instability (MRI) is the source of turbulence in the disk leading to accretion and outflow. A new paradigm

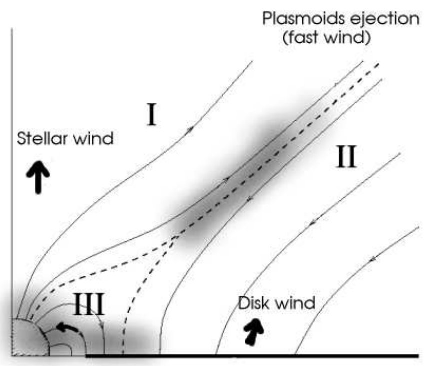
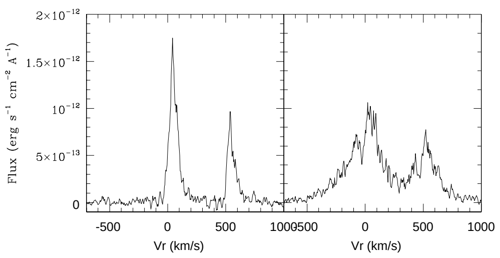


Figure 1:
a) The reference model as described in [9] and adapted from Lovelace et al 1995. Magnetic field lines are represented with the corresponding field orientation.



b) Contribution to the AB Dor C IV[uv1] profile from a normal flare (left) and a transient feature probably associated with a CIR (right). Both events lasted few kiloseconds. The left profile was observed in three events more during the short monitoring time while the last profile was observed only once.
Notice the presence of a narrow absorption and the very broad line wings in the right panel profile (see [3] for more details).

is emerging in the physics of star formation which properly addresses the relevance of the magnetic interaction between the stellar magnetic field and the protoplanetary disk. The interaction disk-magnetosphere basically transforms angular momentum (differential rotation) into toroidal plasmoids which are ejected from the system. Basically all models can be fitted into the basic configuration sketched in Figure 1a; there is a current sheet that separates two distinct regions: an inner *stellar outflow* and an external *disk outflow*. Magnetic flux dissipation is expected to be produced in the current layer leading to plasmoids ejections, as well as to the injection of high energy particles (cosmic rays) in the environment leading to generation of X-rays and ultraviolet radiation. The phenomenon is non-stationary and controlled by two different temporal scales: the rotation period and the magnetic field diffusion time scale. Stellar rotation is a well know parameter which controls the opening of the field lines towards high latitudes however, plasmoids ejection is controlled by *field diffusion* which is poorly determined (see e.g. [7]). In addition, there is direct evidence of infalling gas; the observed velocities are of some few hundreths km s^{-1}, e.g. compatible with free-fall from some few stellar radii. The existence of funnel flows connecting the stellar photosphere with the inner accretion disk has been proposed. The infalling material is expected to release its gravitational energy in the shock at the stellar surface producing hot spots on it.

This outlined paradigm requires to be worked out extensively since many fundamental issues are left opened, for instance,

1. The development of the MRI depends on the effective coupling with the disk, e.g. on the relative density of free charges. The inner region of disks is sufficiently ionized by the stellar X-rays field, but the outer regions are more problematic.

2. There is a timing problem. If we trust that T Tauri systems are alike our early solar system, the meteoric evidence set-up an upper limit of some few 10^7 yr for planetesimal differentiation ([11]). Accretion and outflow are observed in many T Tauri stars 10^7 yr old. How does MRI co-exist with planetesimal formation?.

3. Numerical simulations show that the star-disk-outflow system is self-regulating when various initial disk densities, stellar dipolar field strengths and primordial field associated with the disk are tested ([6]) although strong stellar magnetic fields may disrupt the inner parts of the accretion disk temporarily.

4. The coexistence of several funnel flows is required to explain the correlation between magnetospheric line emission and the accretion rate, however, it is unclear how such a magnetic configuration may be estable and survive in a very active environment.

5. Young stars are very active; rapid variations in the X-ray flux are often detected. However, the source of the X-rays variability is poorly known. In solar and space

plasmas, it is recognized that such rapid variations may be produced by, at least, three very different physical processes: flares, e.g. magnetic reconnection events associated with the solar magnetic activity), corotating interaction regions or CIRs (shock fronts formed in the interaction between the slow and the fast component of the solar wind) and coronal mass ejections. In the star formation context, we often interpret such rapid variations as associated with magnetic reconnection events. However, at least in AB Dor, UV spectroscopy has shown to be able to distinguish between bonna-fidae flares and CIRs (see Figure 1b and [3]). The monitoring was done with the *Hubble Space Telescope* and the old Goddard High Resolution Spectrograph. AB Dor is a 30 Myr old star, in many senses fairly similar to some Weak line T-Tauri Stars as HD283572.

The only way to get into the scale of the structures represented in Fig 1a (from a fraction of R_* to some 10 R_*) is by means of high resolution spectroscopy ($R \geq 30,000$) of warm plasma (from 10,000 to 100,00 K); e.g. high sensitivity, high resolution ultraviolet spectroscopy (see e.g. [4]).

In addition, UV monitorings are instrumental for the study of this highly non-stationary environment phenomena, as well, as to map the structure of the funnel flows. They may also allow us to understand better the physics of cool active stars in connection with the PMS evolution. The existence of large scale magnetic structures, sling-shot prominences, has been proposed to explain the detection of material corotating at some few stellar radii observed in many, rapidly rotating, cool stars (see [2]). In this sense, spectroscopic UV monitorings open the door to the study of the interaction of the stellar wind with protoplanetary disks in the early phases when planetesimals are differenciated and planets form through the formation of corotating interaction regions. Moreover, UV spectroscopy provides fundamental clues on the radiative field in this epoch and its role in the chemical evolution of disk at the time when planets are built. The understanding of PMS stars will allow us to understand better substellar objects.

4.2 The cosmological and chemical evolution of the intergalactic medium up to $z \simeq 2$

Most of the volume of the Universe, and 80% of the cosmic time, is at redshifts less than $z \leq 2$. Studies with 10m class ground-based telescopes have shown that in the first 20% of the Universe metal abundances are of order 1/100th Solar, and suggest- a marginally significant- increase of metallicity by a factor of ~ 2 with time, for the redshift range $3.5 < z < 4$ ([8]). There remains however, a factor of at least 50-100 between the observed [Fe/H] at $z = 2$ and the current epoch is of prime importance. The limited information on this, combined with the essentially total absence of reliable information on the metallicity evolution between $0 < z < 2$, leaves a critical gap in the information needed for the discrimination of the evolutionary models of the Universe (e.g. [1]).

The basic enrichment of the primary material from which the current star formation is drawn is a multifaceted problem in which the IGM plays an essential role. As the formation of heavy elements is, in all current cosmological models, driven solely by processes associated with the life-and-death cycles of stars, and as most star formation takes place in galaxies, the cycling of metals through the Universe must take place on scales which easily exceed the size of galaxies. The IGM contains the material from which the current galaxies have been formed; the recycling of this material after the galaxy and star formation during the period covered by the redshift range from $0 < z < 2$, presents the critical link between our current Universe and the epoch of structure formation.

As the validity of the Hubble classification diagram for galaxies breaks down at $z = 1$ ([10]), it is clear that the answer to the question of the connection between these first epochs of structure formation and the current state of the local Universe can only be addressed in the epochs between $0.2 < z < 1.7$. Only very limited studies have been performed in order to clarify the natiure of the metallicity of the IGM at redshifts $z < 3$. [5] (loc.cit.) showed that the ionization distribution in the IGM is an essential parameter in the abundance determination of this diffuse material. The accessibility of observing at high resolution (R=50,000) and superior S/N for absorption lines associated with the Lyα forest,and Lyman Limit systems ($15 < Log(N(HI)) < 19$), the lines of e.g. OIII-VI, CII-IV, NeIV-VI etc. will permit the exploration of the full range of ionized and neutral gas out to $z = 2$. The resolution is a critical parameter, since it must be sufficient to assure that no component mixing occurs.

The impact of the determination of abundance evolution of the gaseous baryonic content of the Universe at $z < 2$ is especially important at a time that the problem of Star Formation rate in the same redshift range is being addressed by results expected to be obtained with the GALEX survey. The simultaneous availability of information on the methal enrichment processes between $0 < z < 2$ together with the knowledge of the SFR (from the UV-to-SFR coversion) will allow us to constrain the evolutionary models.

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