THE GALAXY EVOLUTION EXPLORER (GALEX): AN ALL SKY ULTRAVIOLET SURVEY

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ABSTRACT. We are preparing a mission to perform imaging and spectroscopic surveys of the sky in the Ultraviolet. GALEX (*The GALaxy Evolution EXplorer*) will fill in the crucial missing piece of the spectrum so that our knowledge of the sky from 100 μm to 10 Å is complete. The Palomar Sky Survey has served as the fundamental resource for research in optical astronomy for over thirty years, and the IRAS, EUVE, and Rosat satellites provided similar databases for the infrared, extreme ultraviolet, and X-ray regimes. GALEX will provide a catalog with an order of magnitude more sources than any of these experiments, and will produce an unprecedented statistically powerful database of UV images and spectra of nearby and distant galaxies, linked to a multiwavelength archive. GALEX is approved as a NASA Small Explorer (SMEX) mission, to fly in 2001.

GALEX will perform a series of spectroscopic and imaging surveys in the space ultraviolet band (1300-3000Å), that will map the history and probe the causes of star formation over the $0<z<2$ range, 80% of the life of the Universe, a period of dramatic evolution, when most stars, elements, and galaxy disks were formed. GALEX will provide a direct measurement of each the redshift (using metal lines and the Lyman break), extinction (using the UV spectral slope), and star formation rate (UV luminosity) in 100,000 galaxies, with efficient slitless grism spectroscopy. It will determine whether rapid evolution has occured in the star formation rate, or in the extinction or initial mass function. The GALEX database will furnish a direct link between rest frame UV properties of galaxies seen locally to those that dominate the faint blue galaxy population. As such, it will provide a framework for the interpretation of the deepest HST images and those that may be obtained by the NGST.

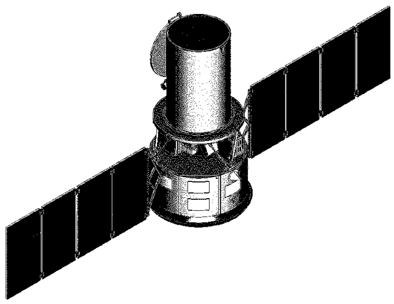

Fig. 1. GALEX

1. Introduction.

The Palomar Sky Survey, the IRAS, EUVE, and Rosat satellites provided powerful databases for the visual, infrared, extreme ultraviolet, and X-ray regimes. Still a comparable resource in the UV, which would have been an ideal "road map" for IUE, HST and FUSE, is not yet available. In the 1200–3200Å range, IUE and the HST spectrographs FOS, GHRS, and STIS provided important results with detailed spectroscopy of selected objects. For detailed compilations of past UV missions we refer to the reviews by Brosh (1998) and O' Connell (1991). See also Bianchi et al (1998a).

JUNO - *The Joint Ultraviolet Nightsky Observatory* (Bianchi & Martin 1994), was proposed by L.Bianchi (Italian P.I.) and C.Martin (USA P.I.) as a bilateral collaboration between NASA and the Italian Space Agency (ASI), to perform the first UV all sky imaging survey and deep imaging and spectroscopic surveys. JUNO was selected in 1993 by both agencies to proceed to the definition phase as a mission of the Small Explorer (SMEX) class. The results of JUNO's definition phase study, completed in July 1994, were evaluated very positively by both NASA and ASI, and great scientific interest and support for the mission was shown by the Italian scientific community. JUNO did not proceed to flight development due to mismatch in the timeframes of the funding profiles of the two Space Agencies, the study however continued and evolved in the currently approved NASA's GALEX mission. GALEX's design draws on the positive experiences acquired with the JUNO study, and the rocket and baloon programs by the CIT and LAS groups, at the same time introducing significant innovations to take advantage of recent technological developement, and to focus on specific high priority scientific goals, described in the next section.

2. Main Scientific Goals of the GALEX mission

Our view of galaxy evolution has changed in the recent few years, with several studies indicating strong evolution of the star formation rate (SFR) as a function of redshift, and the importance of Faint Blue Glaxies (FBG), perhaps tracing the majority of star formation and metal production that ever occurred. An apparent peak in universal SFR in the interval $1 < z < 2$ is suggested by cumulative results from the Canada France Redshift Survey, the Hubble Deep Field and ground based Lyman break galaxy rest UV luminosities (Lilly et al. 1996, Madau et al. 1996, Connolly et al. 1997). Current data (Figure 2) are suggestive of a dramatic peak between redshifts 1 and 2, but rely on numerically limited samples. GALEX will measure redshift and UV luminosity of $\approx 10^7$ galaxies from the Lyman break passing through photometric bands, and directly with follow up spectroscopy of $\approx 10^5$ galaxies.

If dramatic evolution is occurring in the SFR at moderate z, and the UV output is proportional to SFR, then UV-selected galaxy samples should show clear evidence for evolution. A magnitude limited sample of emitting galaxies using the FOCA balloon experiment by LAS (Milliard et al 1992) show that indeed they do. The sample show a high redshift tail, which is direct evidence for the dramatic rise in SFR implied by optical surveys. The UV picture offers a powerful test of evolutionary models because, once extinction is accounted for, the UV luminosity is directly proportional to the cur-

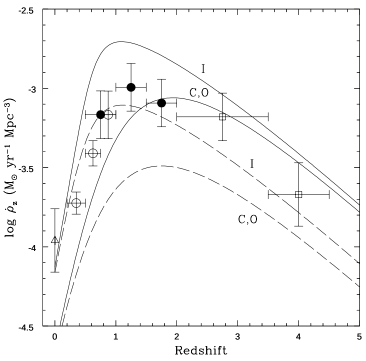

Fig. 2. The Metal Enrichment Rate (directly proportional to the star formation rate) as a function of redshift, from combined sets of measurements (data points) and different model predictions. The Figure is reproduced from Connolly et al 1997, with permission from the authors.

rent star formation rate, in galaxies over a huge dynamic range, unconfused by prior star formation history. The GALEX surveys, alone and augmented by multiwavelength data, will provide a definitive calibration of the UV-SFR relationship, and an accurate accounting for the small to moderate variances to UV-SFR proportionality. This calibration will be crucial for the physical interpretation of high redshift observations of the rest UV emission of young galaxies with HST and NGST.

The primary scientific goals of the GALEX mission will be addressed by a set of focussed, high priority specific objectives, tracing the *origins* of the majority of stars, metals, and many galaxies and galaxy disks, providing the framework for understanding HST and NGST rest UV from high z galaxies, and understanding the drivers of galaxy and QSO *evolution*. The three top GALEX goals will address these questions:

- What are the UV properties of local galaxies, and how do rest UV properties, measured at high redshift by HST and NGST in their search for galaxy *origins*, relate to star formation rate (SFR), extinction, metallicity, and burst history?
- What is the star formation and metal production *history* of galaxies over the redshift range $0<z<2$? When and where did stars and elements see today have their *origins*? And does this history explain the dramatic *evolution* suggested in previous surveys?
- What global (galaxy-wide) factors drive star formation and its evolution in galaxies?

To provide answers, GALEX will produce an unprecedented, statistically powerful database of UV images and spectra of nearby and distant galaxies, linked to a multiwavelength archive. Using UV properties, supplemented by measurements at other wavelengths, GALEX will derive global parameters for each galaxy: star formation rate

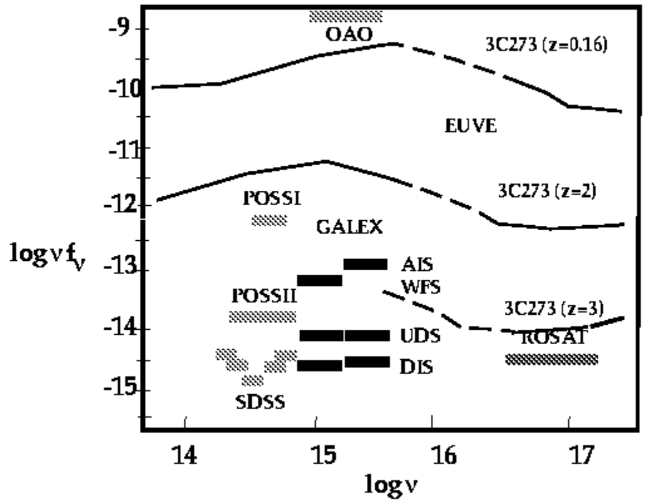

Fig. 3. Completing the survey of the electromagnetic spectrum: GALEX's sensitivity is compared to existing and future sky surveys in the X/Optical/FarUV. From Bianchi et al. 1998a

(from UV luminosity), extinction (from UV slope), initial mass function (IMF), starburst parameters *versus* redshift, and characterize their relationship to galaxies properties (luminosity, type, metallicity, neighborhood, gas supply) and their evolution by comparing statistical distribution of these parameters to cosmological models of the history of galaxies and QSOs.

3. Summary of GALEX mission

The GALEX mission comprises the following phases: an All-sky Imaging complete to about 22 mag_{AB} (2000Å magnitude), a Deep Imaging Survey, covering 200 square degrees of the sky to limiting mag_{AB} 26, and grism spectroscopy (10-20 Å resolution) of wide, medium, and deep fields reaching limiting $mag_{AB} \approx 25$ in the deep fields. The imaging will be obtained in two bands simultaneously: a Near UV band (1350-1800Å) and a Far UV band (1800 - 3000 Å). The Deep Imaging Survey will be significantly deeper in sensitivity than the POSS II, and comparable to the Sloan Digital Sky Survey (SDSS), see Figure 3.

The GALEX imaging survey will be the first complete map of the sky, in two UV bands, with deep sensitivity (background limited), and resolution that allows matching of most (>95%) UV sources with optical sources. As such, it will remain a fundamental resource for a variety of purposes (like the Palomar Sky Survey has been for decades), and a road map for future missions and observations in the UV and other wavelengths.

Tab. 1 - GALEX mission summary

Parameter	Far UV	Near UV
Band	1350-1800 Å	1800-3000 Å
Field of View	1.25 degrees	1.25 degrees
Angular Resolution (80% EE)	2.5-3.5 arcsec	3.5-5.0 arcsec
Detector Pixels	4096^2 (1.1" X 1.1")	4096^2 (1.1" X 1.1")
Spectral Resolution	$\approx$ 10 Å	$\approx$20 Å
$\lambda/\Delta\lambda$	$\approx$ 150	$\approx$ 125
Redshift Range	0<z<1	1<z<2
Redshift Accuracy	$<\pm0.005$	$<\pm0.005$

Tab. 2 - GALEX survey Summary

Survey ($\star$)	Area [deg^2]	Duration [months]	T(exp) [Ksec]	Mag.Limit [m$_{AB}$]	No.Galaxies	N. QSOs
AIS	41,000	4	0.1	$21.7^{a,b}$	10^7	700,000
DIS	200	4	20	$26^{a,b}$	10^6	300,000
WSS	200	4	20	$20.3/22.5^{a,c}$	40K/200K	5K/10K
MSS	20	4	200	$22.0/23.7^{a,c}$	20K/100K	1K/2K
DSS	2	4	2000	$23.3/25.2^{a,c}$	10K/40K	1K/2K
AIP	–	4	–	–		

($\star$) AIS = All Sky Imaging Survey, DIS = Deep Imaging Survey, WSS = Wide-field Spectroscopic Survey, MSS = Medium Spectroscopic Survey, DSS = Deep Spectroscopic Survey, AIP = Associate Investigator Program
(a) AB mag @ 2000Å = -2.5 log f_{nu} -48.6
(b) S/N = 5 (c) S/N = 10, Full resolution / Reduced resolution

A summary of the mission phases and estimated numbers of objects discovered is given in Table 2. The DSS will overlap with the deepest ground-based redshift surveys, since star forming galaxies are 1-3^m brighter in the UV. The DIS will provide two-band imaging 2-3m deeper than the Spectroscopic Surveys, in the same fields. The two UV bands, plus two optical bands, provide enough information to measure a photometric redshift, extinction, and star formation rate (see Bianchi et al 1998a).

The deep fields survey locations will coincide with the SDSS (including the deep southern strip), WIRE, HST HDF, Medium Deep Survey, DEEP fields, and the ACS. The baseline for WSS is two $2^\circ \times 50^\circ$ slices (one North, one South). Also, we hold four months mission reserve.

GALEX's instrument is a 50cm telescope with a dichroic beam splitter to provide imaging and spectroscopy in two wavelength ranges simoultaneously, and uses MCP cross-delay line (XDL) detectors. See Bianchi et al 1998a, and Martin et al 1998 for a description.

Tab. 3 - The GALEX team

Name (a)	Affiliation	Role/Responsibility
Christopher Martin ⋆	Caltech	Principal Investigator
Peter Friedman ⋆	Caltech	Project Scientist
David Schiminovich ⋆	Caltech	Instrument Scientist and SODA
Barry Madore	Caltech	
Genna Kanner	AUSD	
Luciana Bianchi ⋆	JHU	Science Data Archive
Alex Szalay	JHU	
Tim Heckman	JHU	
Bruno Milliard ⋆	LAS, F	Optics
Jose Donas	LAS, F	
Michael Rich	CAL	
Roger Malina	UC Berkeley	
Oswald Siegmund ⋆	UC Berkeley	Detectors

(a) ⋆ indicates science team members which are also part of the GALEX Management team (with roles as indicated)

CIT provides the leadership, Instrument calibration, SODA, Science analysis and Operations, the UBC group provides the detectors, LAS provides the gratings, JHU (L.Bianchi) will provide the science data archive and interface with the multiwavelength archive, JPL/IPAC provides instrument management, Design, Telescope, DPU, Outreach. UPRM will provide the X-band downlink service, OSC the spacecraft.

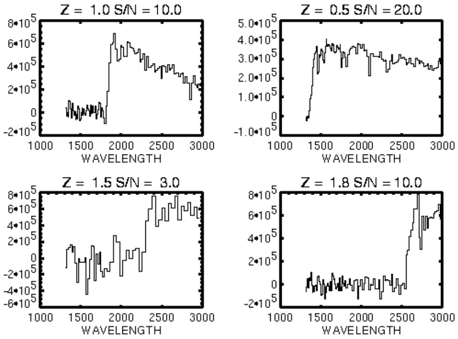

Fig. 4. Panels show simulated GALEX spectra of galaxies at various redshifts and signal-to-noise ratios. Absolute SFR are derived from the measured UV flux and redshift. GALEX obtaines redshifts, for $z > 0.5$, in the most anambiguous and sensitive method available: the Lyman continuum break. Even with low resolution and low S/N spectra, accurate redshifts will be obtained. Figure from Bianchi et al 1998a. For z $<$ 0.5 the metal lines correlation technique is used to determine redshift.

4. Extragalactic science from the UV survey

Specific objectives to answer the science goals described in the previous section will be achieved by the following measurements:

- **Imaging**: Two imaging surveys in a Far UV band (1350-1800Å) and Near UV band (1800-3000Å) with $3''$ resolution and $< 1''$ astrometry, and a cosmic UV background map.
  $\star$ AIS: An All-sky Imaging Survey to 21.7^m (AB), netting $\approx$ 10,000 galaxies within 70 Mpc and an unbiased local calibration of UV galaxy morphology, SFR, and extinction.
  $\star$ DIS: a Deep Imaging Survey over 200 square degrees to 26^m (AB) to provide photometric redshifts, extinction and SFR for the faintest and most distant galaxies.

- **Spectroscopy**: Three overlapping objective-grism Spectroscopic Surveys over the 1350-3000Å band with $\lambda/\Delta\lambda \approx 150$, resulting in measurements of redshifts ($0< z < 2$), extinction, and SFR, for >100,000 galaxies, with **no follow up required**.
  $\star$ WSS: A Wide-field Spectroscopic Survey to 20-22^m (AB) over 200 square degrees to calibrate the global UV/SFR/Extinction relations and find the rarest and most-luminous star-forming galaxies.
  $\star$ MSS: A Medium-deep Spectroscopic Survey to 22-24^m (AB) over 20 square degrees to find star forming galaxies of intermediate SFR and redshift.
  $\star$ DSS: A Deep Spectroscopic Survey to 23-25^m (AB) over 2 square degree to find the galaxies with the lowest SFR and highest z, overlapping the deepest ground-based surveys.

The GALEX spectroscopic survey provide a direct measurement of each the redshift (using metal lines and the Lyman break, see figure 4 and Bianchi et al. 1998a), extinction (using the UV spectral slope), and star formation rate (UV luminosity) in 100,000 galaxies, with efficient slitless grism spectroscopy.

GALEX will also produce a catalog of high redshift QSOs visible in the rest EUV, suitable for the HeII Gunn-Peterson test, providing the spatial distribution of QSOs (evolution of large scale structure, $\approx$ 20 Mpc comoving separation granularity). Information of QSOs evolution will also come from the Variability Survey (see Section 7).

5. Stellar Astronomy and Galactic Extinction from GALEX

With the GALEX database, cross-correlated with optical bands, it will be possible to also:

- Determine the three-dimensional distribution of extinction in the Galactic disk. Several hundreds MS stars will be present in each low b square degree field that can be used to map the 3D distribution of extinction with a linear resolution of $\approx$ 10pc out to 1.5Kpc (B8-A5), and $\approx$ 50pc out to 5Kpc (O-B5), and the UV extinction at high b on a scale of $20'$ using stars.

- Classify hot stars by luminosity and temperature. It is important to notice that our choice of bands allows to separate different types of objects in color-color diagrams (see Figure 5, and Bianchi et al 1998a).
- Place strong constraints on the luminosity functions of a variety of hot objects
- Discover rare hot objects of various source density and luminosity using only the AIS database and optical ID's.
- Separate stars and QSOs at high Galactic latitude (see Figure 5).
- Post-main sequence evolution. The GALEX sources will populate the hot stars HR diagram with enough objects to furnish statistically sound conclusions about the lifetime of each state and its relationship to others.
- Binary-star evolution. Key phases of close binary evolution produce copious UV emission that is diagnostic to the critical parameters, including the presence and mass flux of accretion disks, and the presence of compact non-accreting post MS stars. The AIS will identify thousands of CV's photometr and several hundreds will be included in the spectroscopic sample.

The two UV GALEX bands provide an essentially extinction independent measure of the source temperature, see Bianchi et al 1998a. With optical magnitudes combined, GALEX magnitudes provide Galactic extinction, temperature and UV luminosity, and classification of objects by astrophysical class.

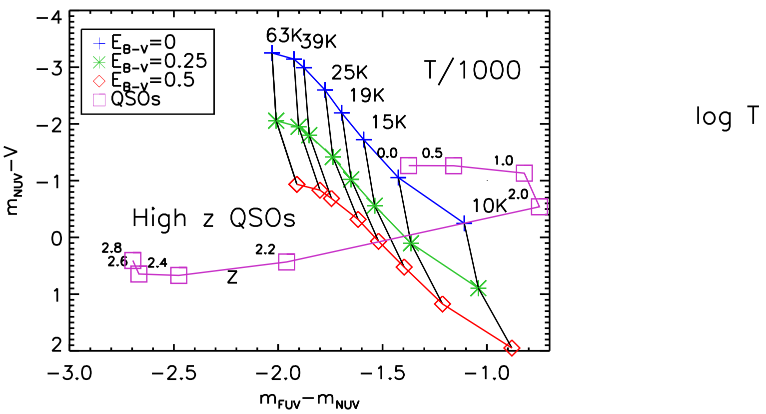

Fig. 5. Two GALEX UV bands plus an optical counterpart provide an independent measurement of continuum temperature and Galactic extinction. QSOs at z >0.5 (squares) are well separated from high b stars, and can thus be selected with high efficiency. $m_{FUV} - m_{NUV}$ colors for QSOs are statistical, with medians as shown. Figure from Bianchi et al 1998a.

6. The cosmic UV background

The GALEX Imaging Surveys (AIS/DIS) will also provide a definitive measurement of any extragalactic UV background. The AIS/DIS will provide a map of the diffuse galactic light which is dominated by dust scattered starlight. We will compare it to HI, IRAS, CO, and Hα maps on all spatial scales and accurately model and subtract dust-scattered starlight, H2 fluorescence, and 2-photon continuum. The NUV map will provide the best zodiacal light model to date. Any isotropic component with no Galactic counterpart is an excellent candidate for extragalactic component. Using the UV/SFR calibration, this can be translated into a global census of the total star formation in all galaxies over the $0<z<2$ range. Luminosity-dependent evolution models predict that the DIS will resolve $\approx$ 70-95% of the extragalactic component, which can be further extrapolated using fluctuation analysis. If direct census of the UV luminosity budget is smaller than the large scale background offset, then we will have evidence for a new, likely extragalactic component, that could not be detected in any other way.

7. GALEX Science Data Products. The GALEX archive

The GALEX data products will be:

- the image of the whole sky in the two UV bands (SkyMap),
- the All-sky Imaging Catalog, with positions, UV magnitudes (two GALEX bands) cross correlation with known objects and relative information at other wavelengths, source profile and postage stamp image.

  The AIS catalog will contain: $\approx 10^6$ QSOs, $\approx 10^7$ spiral/irregular galaxies, $\approx 10^4$ elliptical, $\approx 10^3$ galaxy clusters, $\approx$ 3 x 10^5 hot white dwarfs, $\approx 10^5$ horizontal branch and sD stars, and $\approx 10^4$ cataclismic variable stars.
- UV Images of resolved nearby galaxies
- the Spectral Catalog, containing some 10^5 spectra, with reference data for the objects from the Point Source Catalog or Extended Source Catalog.
- Subcatalogs of objects classified by astrophysical classes with cross-reference identifications to known objects,
- a Variability Catalog obtained by re-examining all the photon-counting data for each point source catalogued after the reconstruction of the sky image. The DIS *variability survey* will contain $\approx$10-300 photometric measurements of every object spaced over 8 months.

In a few years, it should become easier to handle and browse large volumes of data. Powerful statistical searches for objects with given combinations of [multiwavelength] parameters over large areas of the sky will be possible, allowing to exploit effectively all the potential for discoveries and unprecedented information contained in the UV sky. The availability of multiwavelength, terabyte size, archives from GALEX and other survey projects will open a new way of doing science, with broad archive-centered research projects. But complex, multiparameter queries of terabyte-size archive are not possible with traditional indexing techniques. A new archive architecture (multi-dimensional tree-structure organization of the data that will allow a course-grain map of indexing parameters) will allow complex queries to be performed on large databases, and to link databases at different wavelengths. The GALEX archive concept is described in Bianchi et al (1998b). The archive structure will exploit development already undergoing for the SDSS (Szalay 1997), and is being adopted by other projects as well. This will ultimately allow to link archives from different projects. The multiwavelength archive, which will evolve in the conceptual “Digital Sky”, will link GALEX to other archives, supported separately but that will share a common structure and seamless cross-referencing scheme. GALEX will provide 2 bands, SDSS will provide 5 bands, 2MASS 3 bands, and FIRST 1 radio band. GALEX and SDSS will also provide tens of millions of spectra.

Acknowledgements

The author is very grateful to Mark Dickinson for kindly providing Figure 3 of Connolly et al (1997), and for useful discussions.

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