Session IV

Galaxy Evolution and Clusters of Galaxies

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The Galaxy Evolution Explorer – Early Data

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Abstract. We report on early data from the Galaxy Evolution Explorer (GALEX), a NASA Explorer Mission launched on April 28, with a nominal mission start of June 19. GALEX is performing the first space UV sky-survey, including imaging and grism surveys in two bands (1350–1750 Å and 1750–2800 Å). The surveys include an all-sky imaging survey (limit AB$\sim$20–21), a medium imaging survey of 1000 sq. deg (limit AB$\sim$23.5), a deep imaging survey of 100 deg^2 (limit AB$\sim$25.5), and a nearby galaxy survey. Spectroscopic grism surveys (R=100–300) will be performed with various depths and sky coverage. Many targets overlap existing or planned surveys, including SDSS, DEEP, NOAO-DWS, VIRMOS, SWIRE, SINGS, SIRTF-GTO, Chandra, and HST/ACS. We will use the measured UV properties of local galaxies, along with corollary observations, to calibrate the UV-global star formation rate relationship in galaxies. We will apply this calibration to distant galaxies discovered in the deep imaging and spectroscopic surveys to map the history of star formation in the universe over the redshift range 0<z<2. The GALEX mission will include a Guest Investigator program for primary observations and supporting data analysis. This will support a wide variety of investigations made possible by the first UV sky survey.

1. Science Overview

With GALEX we seek to study the UV properties of galaxies in the local universe. We will measure the relationship of UV to star formation rate, extinction, starburst history, initial mass function, and metallicity. We will do this using studies of nearby, spatially resolved galaxies, and in large samples of more distant low redshift galaxies. We will combine UV images and spectra with data obtained from the Sloan Digital Sky Survey, 2dF, 2MASS, IRAS, ISO, and a suite of nearby galaxy surveys to determine the definitive relationship between global UV properties and physical properties of galaxies.

Using this local "calibration", we will study distant galaxies over the redshift range $0.3 < z < 2$ to track the cosmic star formation history, the history of extinction, modes of star formation, and the starburst history of the universe, over a cosmic time of roughly 10 Gyr.

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Finally, we will generate a legacy data set which will support studies of the statistical properties and evolutionary history of quasi-stellar objects, post-main-sequence stars, and degenerate binary stars. A large database will definitely resolve the nature of the UV rising flux in early-type galaxies. High redshift QSOs visible in the observed FUV and NUV will determine the rest EUV spectral energy distribution of quasars and provide sources for IGM studies with the HeII Gunn-Peterson test.

GALEX addresses these goals with a set of imaging and spectroscopic surveys. Five imaging surveys are underway in a Far UV band (1350−1750 Å) and Near UV band (1750−2800Å) with 4.5−6 arcsecond resolution (FWHM) and 1 arcsecond astrometry, and a cosmic UV background map. Three overlapping slitless-grism spectroscopic surveys over the 1350−2800 Å band with $\lambda/\Delta\lambda \sim 100$, resulting in greater than 100,000 galaxies with redshifts ($0 < z < 2$), extinction, and SFR.

AIS: An All-sky Imaging Survey to 20−21 mag (AB), netting 10,000 galaxies within 70 Mpc and 10 million galaxies overall for an unbiased local calibration of UV galaxy morphology, SFR, and extinction.

MIS: A Medium Imaging Survey over 1000 deg^2 to 23 mag (AB) to provide data on galaxies at intermediate distances and luminosities. Large overlap with SDSS.

DIS: A Deep Imaging Survey over 80 deg^2 to 25 mag (AB) to provide photometric redshifts, extinction and SFR for faint and distant galaxies. DIS regions will overlap SIRTF Legacy SWIRE fields.

UDIS: An Ultra-deep Imaging Survey over 4 deg^2 to 26 mag (AB) to provide photometric redshifts, extinction and SFR for the faintest and most distant galaxies.

NGS: Nearby Galaxy Survey of 150 nearby galaxies with exposures of 1−2 orbits per galaxy. Large overlap with the SIRTF SINGS program.

WSS: A Wide-field Spectroscopic Survey to 20 mag (AB) over 80 deg^2 to calibrate the global UV/SFR/Extinction relations and find the rarest and most luminous star-forming galaxies. WSS will overlap DIS fields.

MSS: A Medium-deep Spectroscopic Survey to 21−23 mag (AB) over 8 deg^2 to find star forming galaxies of intermediate SFR and redshift.

DSS: A Deep Spectroscopic Survey to 22−24 mag (AB) over 2 deg^2 to find the galaxies with the lowest SFR and highest z, overlapping the deepest ground-based surveys.

Four months of dedicated Guest Investigator observations spread over FY2005 will be performed for science complementary to the primary survey goals.

2. Mission

Table 1. Survey Summary

Survey	Area [deg^2]	Expos [ksec]	m_{AB}	#Gals (est.)	Volume [Gpc^3]	$< z >$
Wide Spectro.(WSS)	80	40	20	10^{4-5}	0.03	0.15
Nearby Galaxies (NGS)	—	0.5	27.5[1]	100	—	–
Medium Imag. (MIS)	1000	400	23	3×10^6	1	0.6
Medium Spectro. (MSS)	8	400	21.5[2]	10^4	0.03	0.3
			23.3[3]	10^5	0.03	0.5
Deep Spectro. (DSS)	2	2000	22.5[4]	10^4	0.05	0.5
		2000	24.3[5]	10^5		0.9
Deep Imaging (DIS)	80	40	25	107	1.0	0.85
Ultra-Deep Imag.(UDIS)	1	200	26	3×10^5	0.05	0.9

[1]mag. sq. arcssec; [2]R=100; [3]R=20

GALEX is performed with a wide-field (1.2 degree) UV-optimized instrument consisting of a 50-cm modified Ritchey-Chrtien telescope, a selectable imaging window or grism, a dichroic beam splitter and corrector, a far ultraviolet and near ultraviolet sealed tube microchannel plate detector, and support electronics. A summary of on-orbit performance is given in Table 1. The instrument is coupled to an Orbital Sciences Corporation spacecraft that is three-axis stabilized, with fixed GaAs solar panels, a NiH battery, an X-band transmitter and S-band transmitter and receivers.

GALEX was launched by a Pegasus-XL vehicle on April 28, 2003 into a 29 degree inclination, 690 km circular orbit. GALEX began nominal operations on August 2. The eight surveys listed in Table 2 will be performed concurrently for the first 28 months. Starting October 2004 33% of the mission time will be devoted to the Guest Investigator Program. The mission design is simple. All science data is obtained only on the night side. On the day side of each 96 minute orbit, the satellite will face the solar panels toward the sun. As the satellite enters twilight, it will slew to one of the survey targets. The imaging window or grism will be selected for imaging or spectroscopic targets. If the target is spectroscopic, the grism rotation will also be selected. Once the target is reached, the detector high voltage will be ramped and the target observed.

All observations are performed in a pointed mode with an arcminute spiral dither. AIS targets are obtained with 10 linked pointings per eclipse. Dithering is performed to average over detector non-uniformities and to prevent microchannel plate detector gain fatigue by UV bright stars. Current detector countrate constraints limit localized sources to less than 5 kcps. During science data collection, individual photon events are collected by the far ultraviolet and near ultraviolet detectors and front-end electronics, formatted by the instrument Digital Processing Unit, and stored on the spacecraft solid-state tape recorder along with housekeeping data. At the end of orbital night, detector high voltages are ramped to idle levels to protect them from damage and the spacecraft returns to solar array pointed attitude. Up to four times per 24 hour day the solid state

Table 2. GALEX On-Orbit Performance

Effective Area	20–50 cm^2
Angular resolution	4.5–6″FWHM
Spectral Resolution	100–250
Field of View	1.2 degrees
Bands (simultaneous)	FUV 1350–1750Å; NUV 1750–2800Å
Sensitivity	100 s 20.5 [AIS]
(AB mag)	1 ks 23.5 [MIS/NGS]
	30 ks 25.5 [DIS]
Observations	Nighttime–1 eclipse=1000–2000 s
Mission Length	Baseline 28 months, Minimum 12 months

recorder is dumped via the X-band transmitter to ground stations in Hawaii or Perth, Australia, operated by Universal Space Networks (USN). Real-time satellite health and safety monitoring is performed by the Mission Operations Center (MOC) at Orbital Sciences Corporation in Dulles, Virginia, during the ground pass. Science telemetry is shipped by ground network to the Science Operations Center at Caltech, with a latency of 4 hours for housekeeping and 48 hours for photon data. Science data will be processed at Caltech to produce images, object catalogs, and extracted spectra. Catalogs and spectra will be delivered to the Space Telescope Science Institute to be archived in a database developed by Johns Hopkins University for the Sloan Digital Sky Survey (SDSS).

The GALEX instrument uses a novel optical design using a modified Ritchey-Chrétien telescope with four channels, including FUV and NUV imaging, and FUV and NUV spectroscopy. The FUV and NUV bands are obtained simultaneously using a dichroic beam splitter that also acts as a field aberration corrector. The field of view is 1.2 degrees circular. The telescope has a focal length of 3 meters, and is coated with Al-MgF_2. Imaging, grism, and opaque modes are selected with an optics wheel with a CaF_2 Imaging window, a CaF_2 transmission grism and an opaque position. The grism position angle may be selected with a resolution of 0.3 degrees, independent of spacecraft roll. Spectroscopic observations are obtained at numerous different position angles to remove spectrum overlap effects. The beam splitter/asphere is an ion-etched fused silica plate with aspheric surfaces on both sides. Beam splitting is accomplished with a dielectric multilayer on the input side which reflects the far UV band (1350–1750Å) and transmits the near UV band (1750–2800Å). The far UV detector is preceded by a blue edge filter with blocks OI 1304,1356 Å, and Lyα. The near UV detector is preceded by a red block filter/fold mirror, which produces a sharper long-wavelength cutoff than the detector CsTe photocathode and thereby reduces the zodiacal light background and optical contamination. The detectors are sealed tube Z-stack microchannel plates with crossed delay-line anodes The far UV detector has a MgF_2 window which includes power for field flattening, and an opaque CsI photocathode. The near UV detector has a Fused Silica window which also includes power for field flattening, and a semi-transparent Cs_2Te photocathode proximity focused across a 300 μm gap. The detector peak QE is 12% (FUV) and 8% (NUV). The detectors are linear up to

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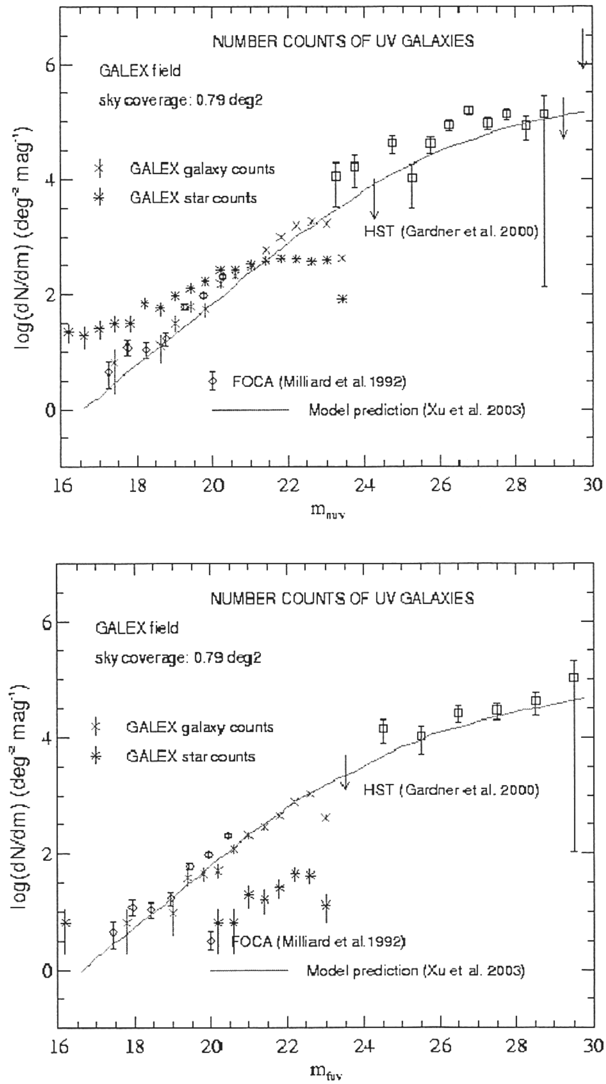

Figure 1. Number counts of galaxies and stars measured by GALEX in NUV (Top) and FUV (Bottom) compared with previous measurements. Results plotted are for a single MIS field (1 deg^2).

a local (stellar) countrate of 100 c/s, which corresponds to m$_{AB}$ $\sim$ 14-15. The system angular resolution is typically 4.5/6.0 (FUV/NUV) arseconds (FWHM). The grism spectral resolution is 200/100 (FUV/NUV). On orbit angular resolution and instrument throughput are as expected from ground calibration. A more complete description of the instrument and satellite can be found in Martin et al. (2003).

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The GALEX data analysis pipeline operated at the Science Operations Center receives the time-tagged photon lists, instrument/spacecraft housekeeping and satellite aspect information within two days of the ground contact. From these data sets, the pipeline reconstructs the aspect versus time and generates images, spectra and source catalogs. The first pipeline module corrects the photon positions for detector and optical distortions and uses a maximum-entropy algorithm to calculate an optimal aspect solution based on the time-tagged photon data. A photometric module accumulates the photons into count and intensity maps and extracts sources from images. A spectroscopic module uses image source catalog inputs to extract spectra of these sources from the multiple slitless grism observations. Realistic processing simulations indicate that eight installed 1–2 GHz dual processor servers running under the Linux operating system will process the complete set of data from a 24 hour period in considerably less than the 12 hour maximum requirement.

3. Early Data

3.1. All-sky and Medium Imaging Survey

GALEX AIS and MIS catalogs in fields overlapping the SDSS DR1 were matched to SDSS objects. In a single MIS fields, more than 2000 NUV objects have SDSS matches, with 900 FUV counterparts. From this, roughly 75 are galaxies with spectra, with 21 spectroscopic QSOs. These, in combination with SDSS PSF star/galaxy separation, show that color-color distributions in $NUV - g$, $g - r$ give good separation of stars, QSOs, and galaxies. Using this color separation at deeper magnitudes, we find that the number counts are in reasonable agreement with prior results, with some evidence for a shortfall in FUV counts compared to FOCA results. This result is plotted in Figure 1.

3.2. Nearby Galaxy Survey

The nearby galaxy survey has obtained images of several dozen galaxies. In Figure 2 we show a comparison of the image of M51 in the UV as measured by GALEX, the visible (Digital Sky Survey) and near infrared (2MASS). The companion disappears in the UV image, and the spiral arms become very prominent.

Figure 3 shows a smoothed and stretched image of M83, which displays low surface brightness UV emission extending far beyond the optical radius of the galaxy. This emission, which has a surface brightness of $\sim 27 - 28$ mag/arcsec^2, is very well correlated with HI as is shown in the figure. Many low surface brightness regions of extended UV emission appear in other nearby galaxy images as well.

3.3. Deep Imaging & Spectroscopic Surveys

Deep Imaging Survey data have already been obtained in a number of regions, including the Extended Groth Strip (EGS), the NOAO Deep Wide Survey field, the ELIAS1 field, VIMOS Deep Survey at 22h, the SIRTF First Look Survey field, and several Lyman Break Galaxy survey fields of Steidel et al. (2003). In Figure 4a we show a 10 by 10 arcminute region of the EGS surveyed by CFRS (Lilly et al. 1995) and the photometric redshift survey of Brunner et al. (1997).

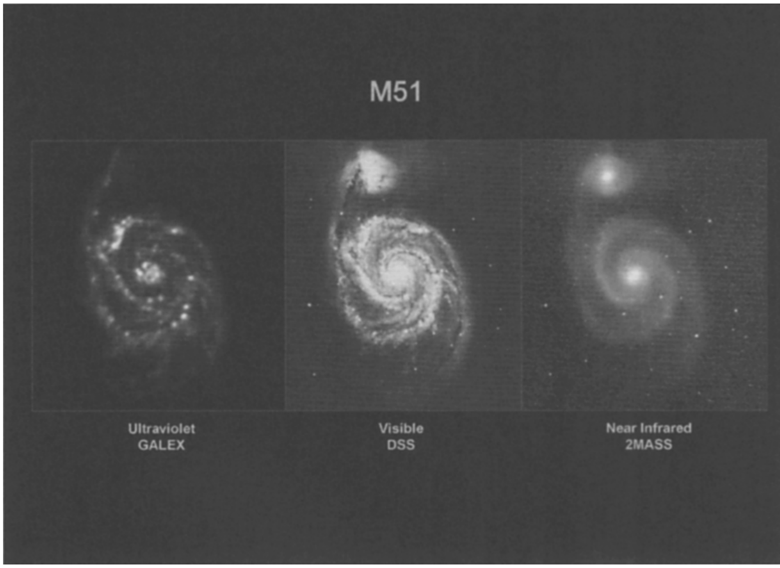

Figure 2. Comparison images of M51. Left: GALEX 2 color (NUV/FUV) image. CENTER: DSS image. RIGHT: 2MASS image.

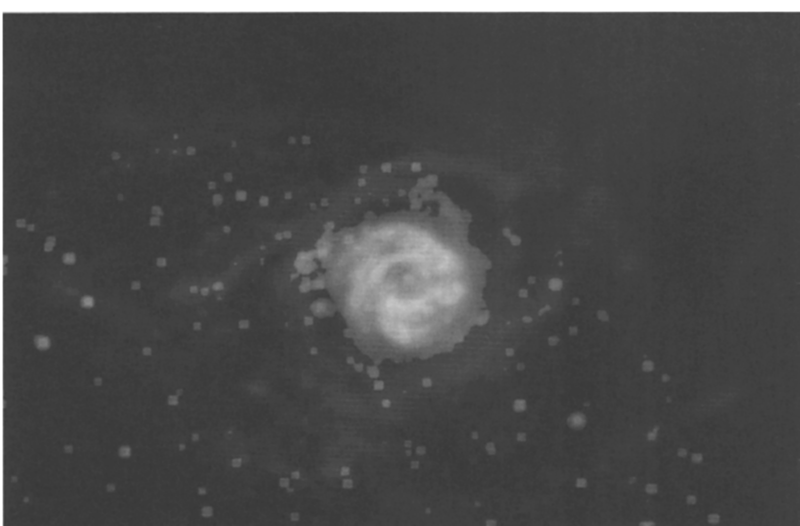

Figure 3. Smoothed and stretched UV image of M83 showing low surface brightness emission correlated with extended HI emission.

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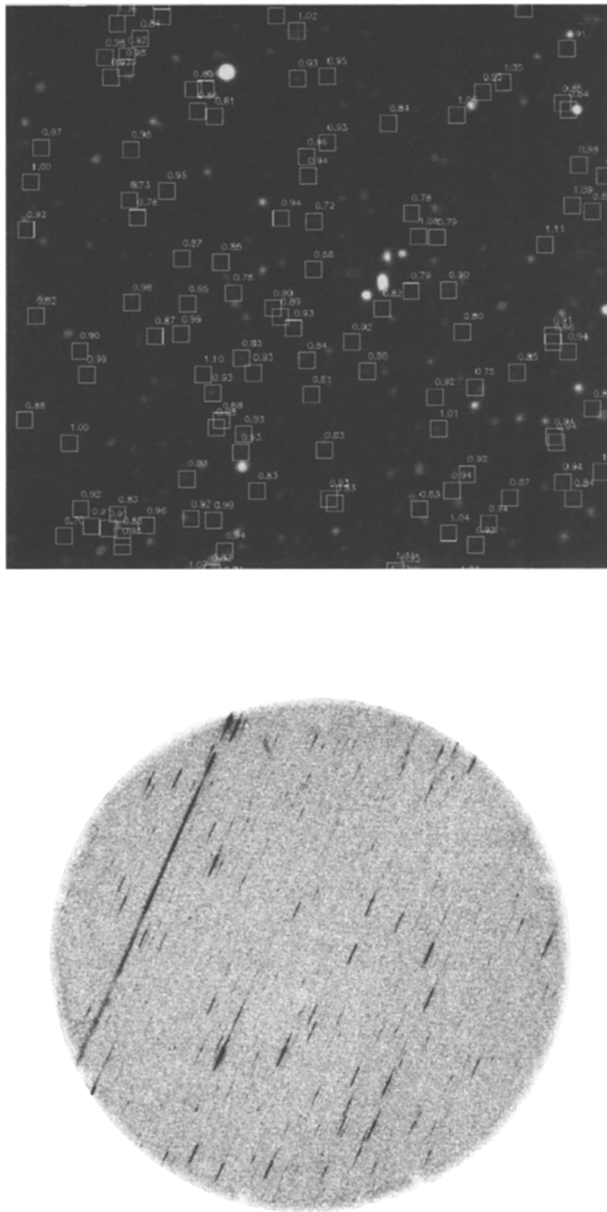

Figure 4. Top: NUV/FUV image of 10 by 10 arcmin region of the Extended Groth Strip. Boxes show objects with photometric redshifts $z > 0.7$ from Brunner et al. (1997). Bottom: Single orbit grism image of the Deep Wide Survey Bootes field.

Objects that are at $z \sim 1$ are detected in NUV with a red FUV-NUV color. More than 200 objects are detected in this small subset of the survey, suggesting that over 10,000 $z \sim 1$ objects per field will be detected, or ~ 1 million over the planned 100 deg^2 DIS. The spectroscopic surveys are underway. Single orbit data from the Deep Wide Survey field is shown in Figure 4b.

4. Data Release and Archiving

An Early Data Release (EDR) is scheduled for late 2003. The Guest Investigator Program (GIP) Announcement of Opportunity will be released in early January 2004. The first major data release (DR1) is scheduled for Fall 2004.

GALEX images and catalogs will be released to the public at the Multimission Archive at Space Telescope (MAST) using a queriable database schema. The GALEX archive design is based on the Sloan Digital Sky Survey (SDSS) SkyServer architecture. This is a natural match, both because the GALEX science depends on SDSS corollary data and since the structure and the format of the data has remarkable similarities to the SDSS (multiwavelength, combination of imaging and spectroscopy, etc.). The Archive will be implemented using Microsoft SQL Server, and much of the front end will be web-based, probably implemented using SOAP and .NET, and adhering to the National Virtual Observatory standards.

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