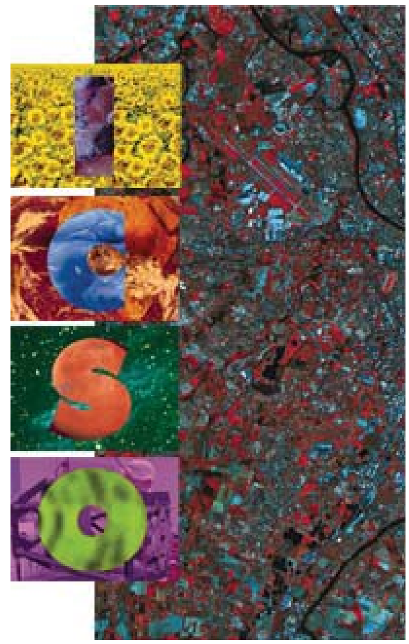
International Conference on Space Optics—ICSO 2000

Toulouse Labège, France

5–7 December 2000

Edited by George Otrio



GALEX: a UV telescope to map the star formation history of the universe

Bruno Milliard, Robert Grange, Christopher Martin, David Schiminovich,

International Conference on Space Optics — ICSO 2000, edited by George Otrio, Proc. of SPIE Vol. 10569
1056912 · © 2000 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2307874

GALEX: A UV TELESCOPE TO MAP THE STAR FORMATION HISTORY OF THE UNIVERSE

Bruno MILLIARD(1) Robert GRANGE(1)
Christopher MARTIN(2) David SCHIMINOVICH(2)

(1) Laboratoire d'Astronomie Spatiale, France - http://www.astrsp-mrs.fr
(2) California Institute of Technology, USA - http://www.srl.caltech.edu

ABSTRACT *- The NASA Small Mission EXplorer GALEX (PI: C.Martin, Caltech) is under development at JPL for launch late 2001. It has been designed to map the history of star formation in the Universe over the redshift range 0-2, a major era where galaxies and gas content evolved dramatically. The expected depth and imaging quality matches the Palomar Observatory Surveys, allowing GALEX to provide the astronomical community with a database of FUV photometric and spectroscopic observations of several million galaxies in the nearby and distant Universe. The 1.24 degree FOV, 50 cm aperture compact Ritchey-Chrétien telescope is equipped with two 65 mm photon-counting detectors. It will perform several surveys of different coverage and depths, that will take advantage of a high throughput UV-transmissive Grism newly developed in France to easily switch between imagery and field spectroscopy modes. A thin aspherized fused silica dichroic component provides simultaneous observations in two UV bands (135-185 nm and 185-300 nm) as well as correction for field aberrations. We shall briefly present the mission science goals, and will describe the optical concept, along with the guidelines and compromises used for its optimization in the context of the "Faster, Better, Cheaper" NASA philosophy, and give a brief development status report.*

1 – GALEX MISSION GOALS

A crucial aspect of the evolution of galaxies along cosmic time is the changing rate to which they create new stars out of the gas stored in their potential wells. This gas is enriched in heavy elements by the internal nuclear reactions that fuel the stars energy output, and is partly recycled during and at the end of the star lives. Tracing the global star formation in galaxies as a function of time is thus a key approach to understanding how chemical element abundances have grown after the relatively limited post big bang chemistry.

The available relevant information has tremendously improved these last five years, owing much to a worldwide effort using observations performed with the Hubble Space Telescope and large ground-based instruments with efficient multiplex spectroscopy (CFHT, Keck, AAT). Various techniques have been used to monitor the global star formation rate at different epochs, and a global picture of how the gas content and the star formation in the universe have evolved since the big bang is emerging (references in [Stei 99]). Among various techniques, the observation of galaxies in the far ultraviolet continuum where the short-lived massive stars release most of their energy, has been successfully used to track the star formation activity in the past with the convenient time resolution of a few hundred million years. For extremely distant galaxies, the rest-frame FUV light is made readily available at ground-based telescopes owing to the Universe expansion that brings it into the visible after a travel time longer than fifty per cent of the Universe age. Paradoxically, it

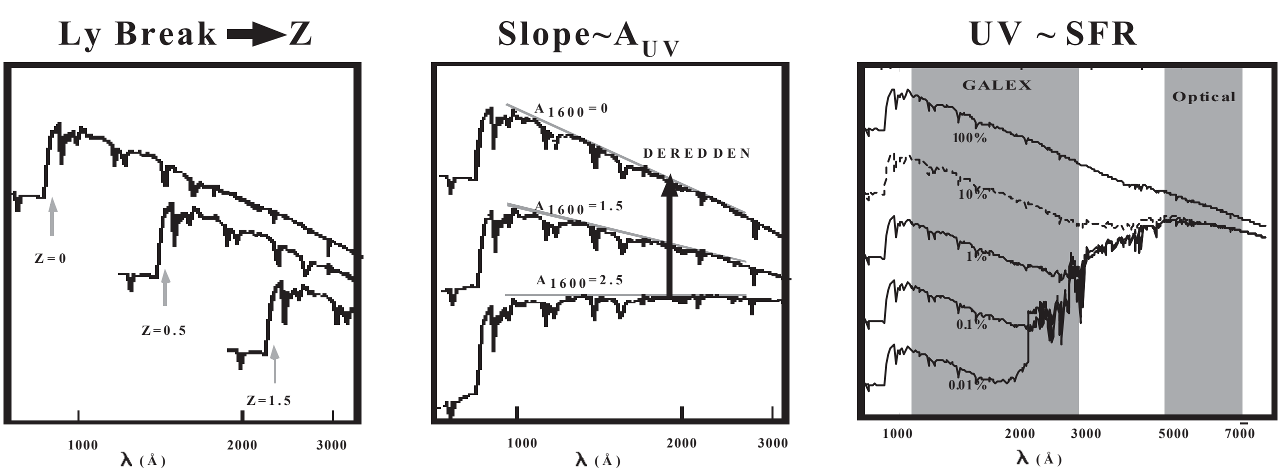
Send offprint requests to Bruno.Milliard@astrsp-mrs.fr

turns out that little information on the rest-frame FUV of galaxies is yet available in the nearby and mildly distant Universe, where the rest-frame FUV is only observable from space instruments. Except the relatively limited data from a few balloon-borne or Space Shuttle FUV imagers, the information on star formation rates in this regime had to rely on different techniques using in particular gas emission lines or Far Infra Red observations at different epochs. This hampered an homogeneous evaluation of the present star formation rate and of its changes over the last seven billion years, a critical era where the star formation activity has most probably drastically decreased [Lill 96].

Galex has been selected late 1997 as a NASA Small Explorer Mission and is planned for launch early 2002. This 28 months in-orbit lifetime project is being developed by a consortium led by Caltech (P.I. C.Martin), and is presently (November 2000) in the process of alignment and qualification at JPL. Galex has been designed to overcome the above limitations in order to provide a systematic census of the present global star formation activity in galaxies, and to track back its evolution over a dominant fraction of the Universe age, with a single homogeneous approach.

2 – GALEX SCIENTIFIC APPROACH

GALEX will perform a series of wide spectroscopic and imaging surveys in the space ultraviolet at a depth comparable to the Palomar Observatory Sky Surveys, to measure the rest-frame FUV continuum of a very large set of galaxies. Low resolution slitless spectroscopy is performed over a significant fraction of the imaged sky to discriminate the quasars and to derive how much the Universe has expanded since the time when the light has been emitted, *i.e.* the redshifts. This is done using the Lyman break, a strong and ubiquitous neutral hydrogen opacity feature below 91.2 nm (Fig. 1 *left*). These redshifts are related to the galaxies distance in a given world model, which in turn yield the absolute FUV energy emitted by galaxies at the epoch corresponding to the light flight time for these distances (lookback time). A UV spectral index can be derived from the



(i) The Lyman break gives an easily detectable, strong, unambiguous red-shift that can be obtained even with low S/N spectra. Thus we derive the position of the galaxy in space, distance, and absolute luminosity.

(ii) Star-forming galaxies have UV spectra with constant slope before extinction. Thus the slope can be used to measure the average total extinction in the UV, and the instrinsic UV flux can be inferred.

(iii) Once the distance and intrisic UV flux is known, GALEX exploits the proportionality of UV luminosity to star formation rate, over many orders of magnitude of activity.

Fig. 1 : The Galex method (see text)

spectroscopy mode observations or from photometry in the two GALEX bands, which will be used to derive corrections for the attenuation by interstellar dust (Fig.1 *center*) [Calz 97]. One can thus retrieve the intrinsic total energy produced in the FUV which is a good tracer of the star-formation intensity over the last 10^8 years in normal galaxies (Fig. 1, *right*) [Sull 00]. GALEX takes advantage of the low FUV background in a 690 km orbit, to detect galaxies up to very large distances with a modest size and angular resolution instrument (a summary of the surveys characteristics is given Table 1). The star formation activity can thus be monitored over the last 80% of the Universe history with a single homogeneous method, a strong advantage to track evolutionary changes. The large expected sample, about ten million galaxies in imaging mode and a few hundred thousand in spectroscopy mode, provides statistical robustness, while allowing to test trends with galaxy parameters like morphology, environment or gas content. The ultimate goal is to understand what global factors drive the star formation activity and its evolution in galaxies.

Survey		Area [deg²]	Length [months]	Mag Lim FUV [μJy / mAB]	Mag Lim NUV [μJy / mAB]	# GALs	GAL <z>
All Sky Imaging (AIS)	S/N = 5	41000	4	15.5 / 20.9	8.5 / 21.6	$10\ 10^6$	0.2
Deep Imaging (DIS)	S/N = 5	160	4	0.1 / 26.5	0.1 / 25.8	10^6	1.0
Wide Spectro. (WSS)	S/N = 10, full res.	160	4	23.0 / 20.5	38.0 / 20.0	15,000	0.2
	S/N = 2, binned			*2.0 / 23.1*	*7.0 / 21.8*	*250,000*	
Medium Spectro. (MSS)	S/N = 10, full res.	16	4	4.0 / 22.3	10.0 / 21.4	10,000	0.5
	S/N = 2, binned			*0.6 / 24.5*	*1.8 / 23.3*	*50,000*	
Deep Spectro. (DSS)	S/N = 10, full res.	2	4	1.2 / 23.7	3.0 / 22.7	10,000	1.0
	S/N = 2, binned			*0.2 / 25.5*	*0.6 / 24.5*	*20,000*	
Associate Investigator Pgm (AIP)			4				
Margin			4				

Table 1: Galex surveys main characteristics. Covered area *(col.2)*, survey duration *(col.3)*, FUV & NUV sensitivities *(col.4 & 5)*, expected number of detections *(col.6)*, average redshift *(col. 7)*.

Although the analysis of Galex observations will be strongly enriched by data at different wavelengths (namely SDSS, SIRTF), the basic information on the star formation history can be retrieved from measurements performed with GALEX alone, which alleviates for the shrunk samples with poorly known selection criteria that often result from cross-mission identifications. The complete reduced catalogs will be made publicly available through the Internet as soon as calibrated. Some additional information can be found on the public Galex Web site at the address *http://www.srl.caltech.edu/galex/.*

3 – GALEX TOP LEVEL REQUIREMENTS AND CONSTRAINTS

GALEX is being developed in the frame of a NASA Small Mission EXplorer. This implies very short development times (selection Nov. 97, launch Jan. 2002) and limited funding. This context, attractive by its rapidity, implies drastic choices in the mission design and development, among others: strictly limit the technical developments, use on-the-shelf space-qualified components as often as possible, limit and control the interfaces thus the number of collaborating Institutes, and as much as possible keep simple and robust, with loose tolerances to minimize risk and cost.

The top level science requirements to reach the mission goals have been mostly elaborated from the experience gained while analyzing results from a similar although more modest balloon-borne ultraviolet imager known as FOCA (http://www.astrsp-mrs.fr/private/foca/) and relevant spectroscopic followup data obtained at the Mount Palomar 5 m telescope. Given all these constraints, the main optical parameters have been selected in turn, following the sequence below:

- In-flight angular resolution close to 5 arcsec at 80% encircled energy diameter (thereafter 80%EE) in order to limit confusion of the UV fluxes between nearby objects at the expected depth. For a gaussian point spread function, this corresponds to 3.3 arcsec FWHM. An astrometry at ~1 arcsec rms accuracy should be achieved to limit identification ambiguities in other catalogs.
- Highest possible throughput times field of view (FOV). This number is relevant for surveys speed. The bandpasses must provide efficient rejection of the atmospheric emission lines (Ly α 121.6 nm, Oxygen lines) and low redleaks.

- Possibility of slitless spectroscopy at a spectral resolution close to 150 over the full field of view. This is necessary to measure all the galaxies distances, without biasing by a priori selection criteria from other experiments which may turn out inadequate for FUV observations.
- Full coverage of the 135-300 nm spectral range in imaging and spectroscopic modes, to track the star formation down to large enough lookback times (*i.e.* z~2).

4 – OPTICAL CONCEPT, OPTIMISATION AND TRADE-OFFS

As in most experiments, the detector and guidance performance are major drivers for the optical design. The cost constraints prevented the use of an arcsec-class in-flight guidance, and directed us to post-flight correction of the photon addresses for jitter and drift high [Guil 97] allowed by high time resolution photon-counting detectors. Available with solar-blind photocathodes, these photon-counting devices also guarantee low redleaks. The state-of-the-art led to a 65 mm diameter, ~25 µm FWHM, sealed tube developed at SSL (Berkeley, CA) [Doli 00]. In conjunction with a multilayer dichroic filter in the optical path, a CsI photocathode defines a sharp cutoff to the red side of the FUV channel (135-185 nm), whereas the NUV channel (185-300 nm, CsTe photocathode), is limited by the CsTe drop on the red side and by fused silica on the blue side.

The detector has been attributed 25% of the FUV tolerancing budget, *i.e.* 2 resolution elements in the in-flight FWHM. This choice imposed a focal length close to 3 meters ($50/(3.3 * 4.8\ 10^{-6})$), resulting in a FOV about 1.2 degrees for a 65 mm detector. A 4096 pixels sampling (1 arcsec) was selected for it being technically achievable, not too expensive in telemetry rate, and only adding a small contribution to the in-flight blur (3 pixels in the PSF FWHM).

The available room in the Pegasus cap limited the entrance pupil to about 50 cm diameter, thus offering a focal ratio of 6.

The main Galex instrument parameters are summarized Table 2.

Instrument weight	125 Kgs
Entrance Pupil	50 cm (diameter)
Field of View	1.24 deg.(diameter)
Focal length	3 m
Focal Ratio	F/6
FUV Channel	
Angular resolution	4 arcsec (diameter at 80% EE) 2.6 arcsec (FWHM)
Wavelength range	135-185 nm
Detector	65 mm Cross Delay-Line, Photon counting, CsI PK, 4096^2 pixels
Spectroscopy Mode	R ~ 200
NUV Channel	
Angular resolution	4-6 arcsec (diameter at 80% EE) 2.6-3.9 arcsec (FWHM)
Wavelength range	185-300 nm
Detector	65 mm Cross Delay-Line, Photon counting, CsTe PK, 4096^2 pixels
Spectroscopy Mode	R ~100

Table 2: Galex Instrument Main Parameters

A slightly modified Ritchey-Chrétien telescope (Fig. 2) whose astigmatism is corrected by a low power fused silica aspheric plate in the converging beam was found to nicely fulfill all the above requirements in a high throughput, simple, tolerant and compact solution. The aspheric plate bears a multilayer dichroic coating to separate the FUV and NUV light. Its reflecting entrance side corrects the FUV channel. The exit side cancels the entrance side effects and brings the required amount of correction for the NUV. A CaF_2 grism in the converging beam provides the slitless spectroscopy mode and is adjusted to correct for the coma induced by the dispersion in the orders 2 and 1 for the FUV and NUV channels respectively. This is the first grism ever built for the FUV (Grange et al.

this Symposium). The grism can be exchanged with a low power plano-convex imaging window to switch between slitless spectroscopy and imagery modes. The axial chromatism of the transmissive elements is corrected by a slight power on the grism and imaging window entrance faces. Allowance has been made for a small wedge on the aspheric plate to compensate for the coma it induces in the convergent beam.

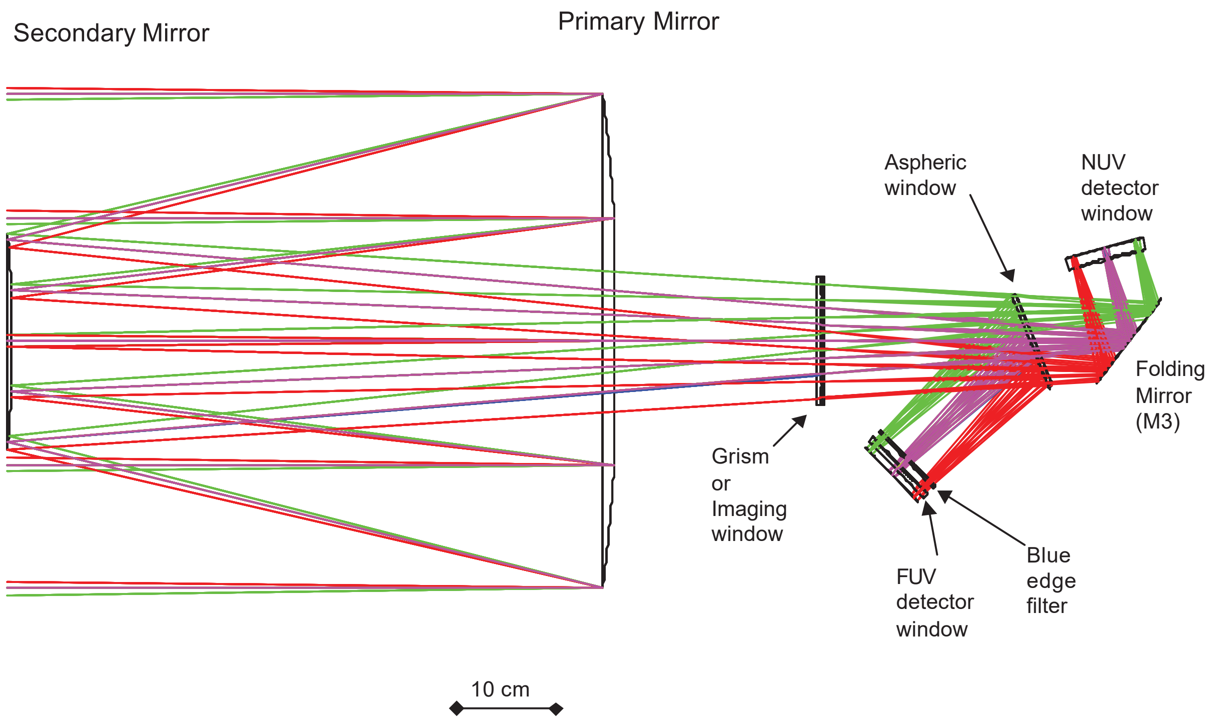


Fig. 2 : Galex Optical Layout

The FUV/NUV dichroic filter deposited on the aspheric window provides simultaneous observation in the FUV and NUV channels which give a high throughput while it improves the out of band rejection. To reinforce the Ly α geocoronal blocking given by the CaF_2, a blue edge filter has been implemented on a thin MgF_2 plate to minimize the atmospheric oxygen lines contribution in the FUV channel. The folding mirror M3 has been multilayer-coated to improve the red side blocking of the NUV channel.

This optical solution provides the required correction over the 1.24 degree FOV in the two channels, both in spectroscopy and imagery modes. It makes use of a limited number of surfaces per channel (3 reflections and 3 transmissive elements for each, including the detector entrance plates and the blue edge filter). To simplify the manufacturing, all the surfaces have been selected plane or conic-shaped, except of course the aspheric. In the same spirit, the aspheric tilt has been kept as small as possible (22 degrees) in order to use a rotationally symmetric aspherization (see Mercier et al this Symposium for the aspheric window manufacturing). The use of a transmissive component for the dispersion allows easy switching between imagery and spectroscopy modes with the help of a single rotation mechanism with loose tolerances, and no need for refocusing between modes.

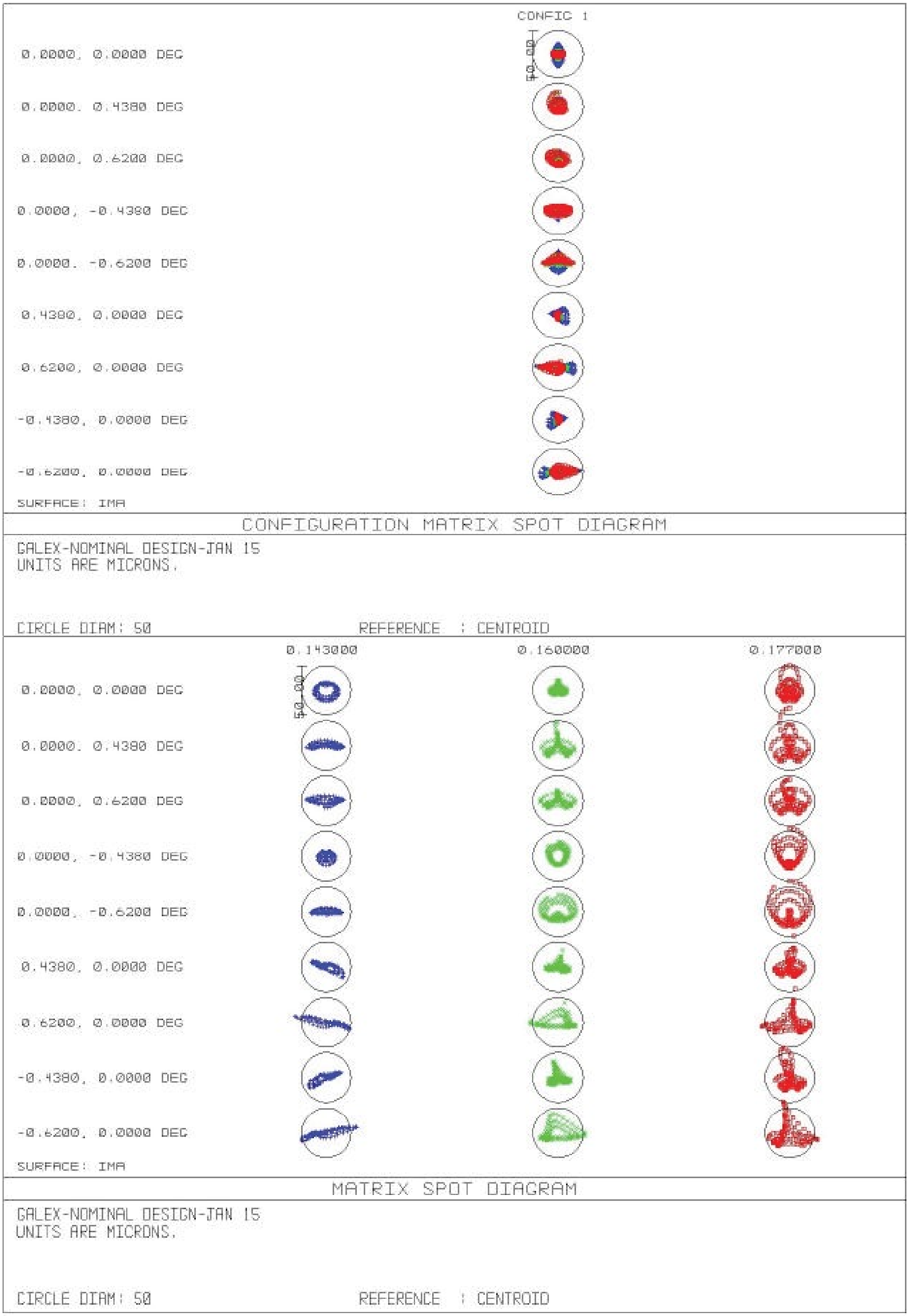


Fig 3. : Spot diagrams for the FUV imagery and spectroscopy modes

The initial design was optimized starting from the FUV channel in imagery mode, because of the higher resolution of the FUV detector. The room needed for the grism drive and the detectors requires an unusually large back focus. Within the available length, this implies a fast primary mirror (f/2) at the expense of more difficult optics, tighter tolerances and more Petzval curvature. At the same time the secondary radius is frozen. The aspheric coefficients of the entrance face are optimized in conjunction with the conic constants of the primary and secondary and the imaging window power, to balance the image quality in the field of view in the whole FUV spectral range. The field curvature is cancelled by the power of the FUV detector window, and the detector is tilted to the best plane. Since the grism must be at the same position as the Imaging Window and the grooves density is settled by the required resolution, the optimization of the FUV channel in spectroscopy mode is to be performed on the only free parameters which are the prism wedge angle (coma compensation) and the prism entrance face power (axial chromatism). The grism works in second order. The NUV channel imagery mode is then optimized with the aspheric coefficients of the aspheric plate exit face, and its wedge. As for the FUV channel, the field curvature is cancelled by the power of the NUV detector window. The last NUV spectroscopy mode with the grism working in first order shows a very good image quality despite the absence of any free parameter to optimize. More, a unique blaze angle on the grism facets is found to provide a well centered efficiency for each channel, owing to the CaF_2 index variation with wavelength. In a final step, all the above parameters have been refined in a multi-configuration optimization, which led to very similar parameters and performance. The spot diagrams for the FUV imagery and spectroscopy modes are shown Fig. 3 top and bottom respectively. The rms spot radius averaged in the FOV is 6.7 µm for the FUV imagery and 10.4 µm for the FUV spectroscopy at 160 nm.

5 – DEVELOPMENT STATUS

Most of the project hardware and software is already assembled. The instrument (Fig. 4) has been

Fig. 4 : Galex under a clean tent at JPL.

optically aligned, and has delivered its first images and spectra in a vacuum tank FUV optical bench. The project is being submitted to qualification environmental tests at JPL, and will be calibrated from December this year to early March 2001 before delivery at Orbital Science Corporation for integration in the satellite.

6 – CONCLUSION

Galex, a space program dedicated to tracking the global star formation history in the Universe over cosmic time, will provide a series of imagery and slitless spectroscopy surveys in two bands in the far ultraviolet.

A slightly modified f/6 Ritchey-Chrétien telescope whose field corrector is an aspheric plate, that makes use of a CaF_2 monocrystalline FUV grism provides a simple, tolerant and efficient optical solution to the mission. The telescope flight model is under adjustment and testing at JPL for a launch scheduled January 2002.

Acknowledgments: Galex is a NASA SMEX program, whose French contribution is funded by the Centre National d'Etudes Spatiales and the Centre National de la Recherche Scientifique.

REFERENCES:

[Calz 97] D. Calzetti "UV Opacity in Nearby Galaxies and Application to Distant Galaxies", In *The Ultraviolet Universe at Low and High Redshift*: Probing the Progress of Galaxy Evolution, W.H. Waller, M.N. Fanelli, A.C. Danks, Editors, 1997, pp. 403-412.

[Doli 00] D.L. Doliber, J.M. Stock, S.R. Jelinsky, J. Malloy, P. Jelinsky, O.H.W. Siegmund, J.S. Hul "Development Challenges for the GALEX UV sealed tube detectors", In UV, Optical, and IR Space Telescopes and Instruments, James B. Breckinridge, Peter Jakobsen, Editors, Proceedings of the SPIE Vol. 4013 March 2000, pp. 402-410.

[Guil 97] M. Guillaume, T. Amouroux, P. Réfrégier, B. Milliard, A. Llebaria "Optimal correlation at low photon levels: study for astronomical images", 1997, Opt.Letters 22, pp. 322-324.

[Lill 96] S.J Lilly, O. Le Fevre, F. Hammer, D. Crampton, "The Canada-France Redshift Survey: The Luminosity Density and Star Formation History of the Universe to Z approximately 1", 1996, Ap.J.L 460, pp. L1-L4.

[Stei 99] C.C Steidel, K.L. Adelberger, M. Giavalisco, M. Dickinson, M. Pettini " Lyman-Break Galaxies at z>~4 and the Evolution of the Ultraviolet Luminosity Density at High Redshift", 1999, Ap.J. 519, pp. 1-17.

[Sull 00] M. Sullivan, M.A. Treyer, R.S. Ellis, T.J. Bridges, B. Milliard, J. Donas "An ultraviolet-selected galaxy redshift survey - II. The physical nature of star formation in an enlarged sample", 200, 00MNRAS, 312, pp. 442-464.