GALEX Lessons Learned

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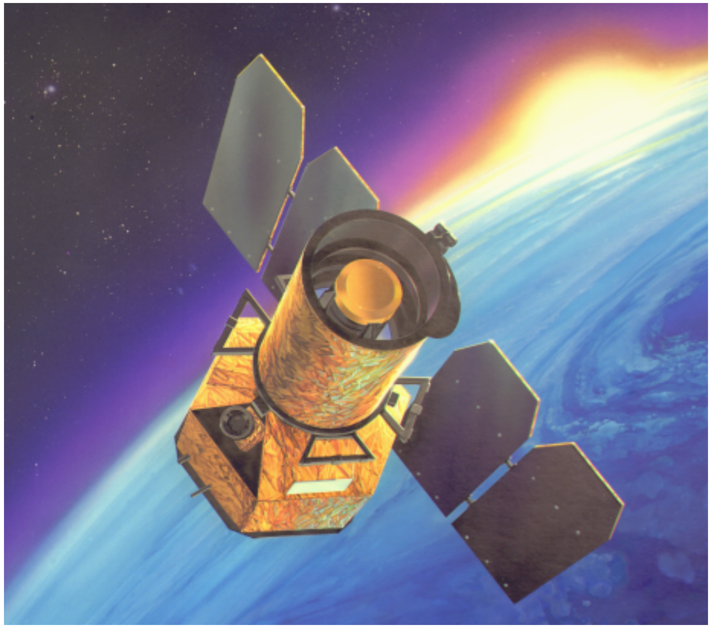
GALEX
Spitzer

GALEX Project Summary

Summary

- NASA Small Explorer Mission (100M$ ΦABCD)
- ΦA Start Dec 1997; Launch 28 April 2003
- Mass 277 kg, Power 293W
- 50 cm ultraviolet telescope
- Large area ultraviolet photon-counting detectors
- Imaging and slitless grism spectroscopy
- 2 bands: FUV (1525Å/300Å), NUV (2200Å/700Å)
- Field of view: 1.24 degree diameter
- PSF diameter: 5” FWHM
- Spectral resolution: 100-250
- Mission Operations: 10 years (2003-2013)
- Guest Investigator Program
- Multiple Large Data releases to MAST



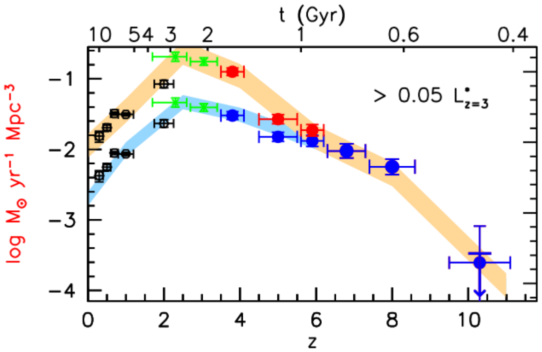
Science

- Map the history of star formation in the Universe over the redshift range $0<z<2$ using nested wide and deep imaging and spectroscopic surveys
- Perform the first ultraviolet all-sky imaging survey (1,000,000 galaxies)
- Perform the first ultraviolet wide-area spectroscopic surveys (100,000 galaxies)
- First deep imaging surveys of the UV universe – 10 Million galaxies
- Sensitivity: all-sky imaging = 20^m; deep imaging = 25^m; deep spectroscopic = $23\text{-}24^m$

GALEX: Galaxy Evolution Explorer Science Overview: Prime Mission

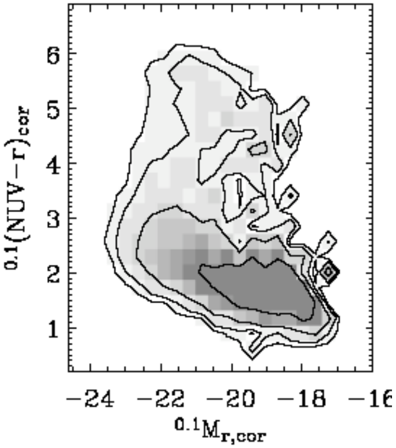
1. standard UV → SFR calibration

2. UV & Star formation history 0<z<1.5

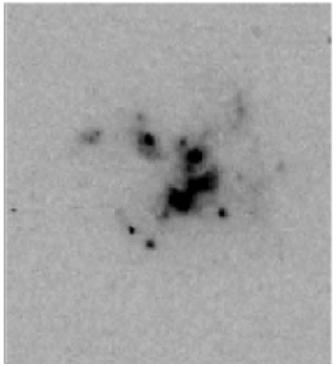


3. Understand SF History

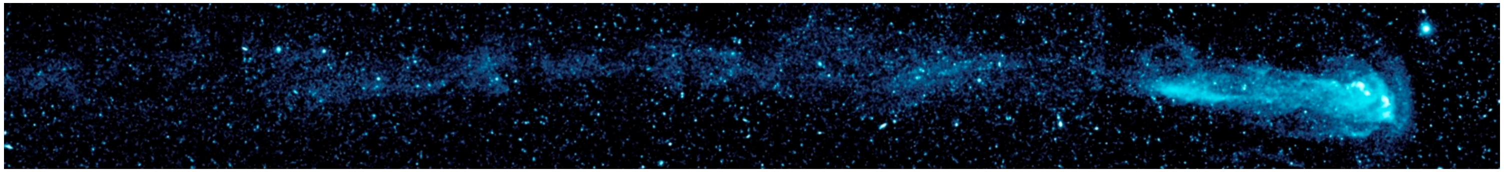
Galaxy “HR”



Star formation in extreme objects



4. Explored the UV sky: AGB star nebulae, black hole stellar disruptions, SNe shock breakout



- **Surveyed the UV sky, reaching flux limits >10,000x deeper than previous all-sky surveys**
- Over 1500 papers, 48,600 citations; GALEX requests dominate MAST archive traffic
- Galaxies evolving from star forming to passive; Evolved star wind nebulae (Mira, CW Leo) recycling into ISM; Stars tidally captured and torn apart by massive black holes; New star formation law at low density; Supernovae breakout shocks; 1st Astrosphere; Most efficient young star finder; QSOs for HST/COS at high z; tidally stripped galaxies; Nova nebula; low mass star formation; high z galaxy analogs; evidence for non-standard IMF; ancient Nova shell; Cosmology (BAO); etc..

GALEX Challenges

Technical

- Large format high resolution MCP detectors (2000 x 2000 over 65 mm diameter) 10x larger than STIS
- Sealed detector tubes
- Dichroic beam splitter design & stability
- Red & blue blocking filters
- Far UV grism
- High throughput, high resolution digitizing electronics
- Large data throughputs (> HST+SIRTF) from detector to data analysis & archiving
- UV telescope with no focus control
- Large thin crystalline optics
- 3 new mechanisms
- Contamination control

Programmatic

- *PI mode*—very limited support from NASA.
- *Cost Cap*—any overrun is grounds for cancellation
- *Shifting programmatic requirements*—NASA became far more risk averse
- *Organization:* Multiple institutions & complex interfaces.
- *JPL*
  - *Learning to do low-cost missions*
  - *Difficult to control costs, many sources of overhead.*
  - *Difficult to sustain stable staffing*
  - *Competition from large missions.*

GALEX Problems (not exhaustive)

- Engineering model Grism ***cracks*** on shake table
- ***Flood after Hurricane*** in Paris, France
- Dielectric coating ***cracking***
- Transmitter company goes ***bankrupt***, X-band transmitter ***fails,*** engineer with ***British/Iranian citizenship***
- FUSE gyroscope ***fails*** in orbit
- Problems getting good MCPs. Problems sealing tubes.
- Electronics PEM ***mysteriously vanishes***
- ***Optics PEM Turnover***
- ***Wrench dropped on primary mirror***
- Detector electronics ***fundamental design flaw***, engineer resigns. Logic design flaws.
- Detector electronics ***mechanical design flaws***
- Detector electronics electrolytic capacitor ***fails after 600 hours,*** 4 found to be in ***backwards.***
- Solar panel company goes ***bankrupt***
- RAD6000 EEPROM ***weak bits***
- FUV02 tube ***sparks*** at high voltage
- Telescope moved in house after vendor ***fails*** to complete. Fundamentally redesigned.
- Fundamental design flaws in S/C electronics FPGAs.
- Telescope ***astigmatism*** and ***focus uncertainty***
- Spacecraft bus ***contaminated*** by pump oil
- Environment test lab filled with ***fine white powder***
- On orbit ***failure*** of Tecstar solar array
- Star tracker cable ***disconnected*** 30 days before launch, fastener ***missing.***
- Apparent ***dropping throughput x10*** just before launch
- The ***Blob***

GALEX Problems (major PI involvement)

- Dielectric coating ***cracking*** ←
- Transmitter company goes ***bankrupt***, X-band transmitter ***fails,*** engineer with ***British/Iranian citizenship***
- FUSE gyroscope ***fails*** in orbit
- Problems getting good MCPs. Problems sealing tubes. ←
- ***Optics PEM Turnover***
- Detector electronics ***fundamental design flaw***, engineer resigns. Logic design flaws. ←
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- Spacecraft bus ***contaminated*** by pump oil
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- Apparent ***dropping throughput x10*** just before launch ←
- Detector ***Blob (high background on-orbit detector feature) and current spikes.***

← PI in lab!

Teaming is Crucial as are Partner Commitments

One of the most important events in the project's history occurs the earliest, in the proposal phase, choosing the major project partners. The choice for instrument: JPL, Ball, Lockheed. The choice for detector: UCB, ???. The choice for spacecraft: Orbital, Ball, Lockheed, CTA. LAM for high performance UV optics. While GALEX team was small, deep bench and institutional commitment in these institutions when problems arose was pivotal.

There were several commitment failures that could have been avoided.

Lesson Learned: We had a superb team.

The choice of JPL to build the instrument and manage the project was ideal because of co-location & teaming, expertise and excellence, and high level management interest in JPL/Caltech cooperation. We would have been a small project in any institution that had a proven track record, and too much of a challenge in any one that didn't. The Science requirement for a sealed, Near UV tube made the choice of UCB for detectors a requirement. UCB had a very good track record, as did Orbital and LAM.

Do not fear making teaming changes early to ensure mission success!

Negotiate partner commitments re: staffing and risk posture (cf. below) early on.

Staffing is Crucial

Our team was excellent at all partner institutions. A balance of experience and youthful enthusiasm, commitment, creativity, proactivity, flexibility, generosity, cross-cutting skills, team spirit. Staff turnover was minimal in most positions. The Project Manager (Fanson) was superb. Keep team motivated by giving them ownership.

Lesson Learned. Form and maintain an energetic team that works well together, that is committed to getting the project done within its constraints in spite of challenges, that is creative and proactive, that is flexible and cross-trained to compensate for the thin bench. Get the best Project Manager you can (or keep trying). Give team members autonomy and authority. *The PI should invest significant time in explaining the science and technology and the importance of the technical and support team in making this science possible to all team members.* Treat people well. A happy team is a happy mission!

GALEX JPL/Caltech Implementation Team

Requirements Definition

The Level 1 requirements were written without specific quantities (except for instrument performance). Level 2 requirements (baseline and minimum) were quantitative interpretations of the L1R. Our performance wrt the mission requirements was constantly under focus particularly by review teams later in the development cycle. The PI was the "Descope Process Owner", although our descope options were highly limited—most were "performance descopes".

Lesson Learned: The PI must have control over the descope process, in order to make the appropriate trades during design, development, and when encountering problems. In order to do that, I tried to generate Level 1 requirements that were true science requirements, but were decidedly unspecific about numbers. I believe that this worked.

Defining quantitative requirements at some level with large margins (especially for the minimum mission) was essential, even though this can be extremely difficult. *Review panels want quantitative metrics* even though we were a cost driven, not requirements driven mission.

Requirements at Level 3 and 4 need to be *prioritized* by performance & risk impacts better than we did, in order to make design & descope decisions.

Make Reviews Value-Added at All Levels

As the NASA risk posture tightened due to multiple mission failures and evolution away from “Faster, Better, Cheaper” reviews evolved from project directed to independent red team (Adversarial) reviews. While additional resources were added and reviews often provided constructive feedback, they were a major drain on a small team with limited time. Often reviewers were not on the same page with respect to acceptable risk levels and program constraints and assigned huge amounts of actions to justify their own existence. On the other hand, informal team level and peer reviews were extremely important.

Lesson Learned: Insist on reviews that are impedance matched to a Small Explorer mission. Involve SMEX-experienced reviewers including PIs, PMs, and System Engineers. Do not let the review process get out of control. Hold many many team-level and peer reviews.

Risk Management

GALEX employed an effective risk management process. Because we had no descope space, we used performance margin as a resource for managing risk. The PI maintained a detailed predictive model of performance, which we used to prioritize our effort based on impacts to overall science capability. The PI and Project Manager worked together very closely to manage risk.

The team placed priority on in-depth understanding of root causes for failures and anomalous behavior.

Lesson Learned: It is possible to effectively manage risk, but it requires technical depth, an environment of openness, and a dogged pursuit of root cause. It is also a fact that risk acceptance is a monotonically decreasing function of time. We found that close to launch it did not matter if a residual risk was higher or lower than other risks we were accepting, what mattered was whether we had done everything possible to mitigate that risk. This aspect of human psychology will very likely have schedule impact late in the game as everyone above you seeks to "re-insure" the risk by holding review upon review, and demanding analysis upon analysis.

Making Early Strategic Changes

Problems are addressed with major focus and strategic changes only after they become very serious, even though they were known risks. We did not have the staffing, or the resources to address them earlier. The HQ development/approval process, cost-cap philosophy, and constant threat of cancellation rewards success-oriented thinking until development has moved past the point of no return.

Example: We had grave misgivings about an outsourced telescope design, yet we proceeded to build it, identifying from day one the perceived risk. This is called "risk management". The outsourced design failed. We had a long period of testing and understanding to try to make the design work until we finally decided to bring it in house at JPL. Even then, we elected to only make a change to the primary mount because of cost concerns. Extensive testing and reviews followed the discovery of problems with astigmatism and focus stability. A replacement secondary was built as a backup, but never flown because of the schedule impact and a successful effort to bound the risk.

Lesson Learned: An early strategic change would have eliminated the telescope as a project issue. While the as built system was in the end adequate, major resources were expended (cost, schedule, personnel, attention) in addressing this problem. Starting from scratch would have been the best decision, but would have raised the threat of cancellation.

Partner/Contractor Insight

Many of our major problems could have been avoided, anticipated, mitigated, or discovered earlier with less schedule impact with various levels of insight by project level engineers, scientists, and Contract Technical Managers. However, the plan in place could not support a high level of CTM oversight. We trusted our partners to meet their commitments. Oversight would not have been readily accepted by most partners, leading to friction and perhaps a less cooperative team.

Lesson Learned: *Trust, but VERIFY*. We should have had 3-5 more CTM/site engineers/site scientists. At UCB, an additional 2-3 scientists/engineers to team on detector heads and electronics to verify design performance, prototype performance, adequacy of staffing.

Perhaps there should be a prenuptial agreement made during the partnering phase (in the bid process) that commits the institution to opening its doors to project level team members for coordination and insight (not oversight) as needed.

Instrument/Systems Engineering Lessons

Lesson Learned:

Distributed Systems Engineering is not optimal. Dedicated (Experienced) Systems Engineer crucial.

Design with modular sub-systems and simple, well-defined interfaces. Develop ICDs early. Test interfaces early.

True heritage/COTs is a fallacy. Every mission is unique.

Requirements flowdown and traceability crucial to optimize development

Build systems that can be modelled (mechanically, thermally, optically).

Build systems that can be tested. Test as you fly. Fly as you test.

Beware descoping lower level tests because higher level tests may have constraints that result in under-testing

Beware polarized capacitors!!!

Build in documentation requirements at the beginning, especially for I&T.

Pegasus launch may be cold and has unusual vibration requirements.

Why was GALEX successful?

- Wide-field survey in band with no survey (x10,000 discovery augmentation)
- Focussed objective with enormous side-benefits
- Richness of UV – physical diagnostics, leverage
- Darkness of UV sky
- Competitive Selection
- Timing – Scientific Landscape
- Synergy with other operating missions (SDSS, Spitzer, HST, Chandra)
- Technology – Taking some risk
  - Large format sealed detectors, dichroic, filters, data volume
- Size – Small; dedicated, talented, young, energetic team; flexibility, PI-led; single, focused agenda.

BACKUP/PROGRAMMATIC LESSONS LEARNED

PI Responsibilities

- Formulation phase
  - Formulated mission design
  - Assembled & organized implementation and science teams
  - Developed Level 1 requirements
  - Led flow-down of science requirements to engineering requirements
- Development phase
  - Worked closely day-to-day in partnership with PM. PM and PI colocated at Caltech with PE, core instrument scientists.
  - Tracked science requirement satisfaction
  - Developed descope plan—descope "process owner"
  - Provided inputs to mission design development & testing plans
  - Constantly monitored status of most subsystem development. Actively participated in peer, project, and program reviews. Constantly asked questions.
  - Hands on role in project critical technical and programmatic issues and problems
  - Developed (w/ PM) replan strategies and presented cases to HQ (3 times)
  - Led science team in development of science analysis plan
- Operations Phase
  - Lead and/or work closely with instrument/SC anomaly response teams
  - Work closely with SODA team in data analysis efforts
  - Lead Science Team in science analysis
  - Communicate GALEX results

PI Experience

- Led development of the following successful space experiments
  - Led EUVE Spectrometer development for several years, experience with large satellite development team
  - Led shuttle experiment to measure UV background
  - Led rocket experiment (thesis) to measure UV background
  - Led rocket experiment to measure OVI from ISM
  - Led rocket experiment to map UV background (NUVIEWS) and perform all-sky UV survey. Many similarities to GALEX.
  - Managed JUNO Phase A study.
- Personal expertise in
  - UV detector development
  - UV optics development
  - UV space astrophysics experiment formulation, design, development, testing, flight, analysis
- Several members of Caltech science team had similar experience
  - P. Friedman, D. Schiminovich, P. Morrissey, R. McLean

Launch Vehicle Provided by Program

The Launch Vehicle was provided by GSFC/KSC through a separate, multi-mission contract (SELVS). Delays in awarding the contract led to delays in definition of the launch vehicle until approximately 1 year after Phase A start. Launch vehicle requirements flow down to countless satellite requirements, starting with the basic mechanical design. Generic requirements were provided but proved inadequate in many cases. Optimizing system design requires trades between Flight, Launch, and Ground systems. Near launch date, problems with LV subcontractor QA and KSC oversight led to significant late term uncertainty.

Lesson Learned: If the PI is not responsible for the LV, a major component of the mission, significant LV impacts on cost, schedule, reserves, and technical risk must be accounted for separately. Trades across satellite/LV boundaries need to be accommodated somehow to maximize mission success. Additional resources must be provided to the PI to accommodate LV impacts.