Proposal Summary

This project will generate a new catalog of unique ultraviolet (UV) sources, screened of significant artifacts, that includes all valid imaging data produced by the Galaxy Evolution Explorer (GALEX), an all-sky survey mission with two UV bands. This data set is unique and extremely valuable; no UV sky survey that is comparable or better in depth, coverage, sensitivity, and precision is planned. Existing catalogs of GALEX sources are incomplete and suffer from a number of artifacts and errors that severely limit their use. The project will reimplement astrometric correction portions of the GALEX mission pipeline and combine those with pre-existing capabilities to entirely recalibrate the GALEX data. The recalibrated data will be used to construct photometrically correct, coadd-depth images of the entire UV sky as observed by GALEX. A new photometric extraction pipeline will be developed and deployed to generate a new catalog of GALEX ultraviolet sources in both bands at visit and coadd depths and which will also address issues in the original mission pipeline with confusion between extended and discrete sources. The resulting extracted photometry will then be screened according to previously developed algorithms to identify unique sources and compiled into a catalog. The GALEX Legacy Catalog (GLCat) will be a high-quality catalog of science-ready UV photometry with improved astrometry, more exposure depth, and higher accuracy and reliability than any GALEX catalog currently available.

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2. Scientific/Technical/Management

a. **Synopsis.** This project will generate a new catalog of unique Ultraviolet (UV) sources, screened of significant artifacts, that includes all valid observational data produced by the Galaxy Evolution Explorer (GALEX), an all-sky survey mission with two UV bands, FUV and NUV. This data set is unique and extremely valuable; no UV sky survey that is comparable or better in depth, coverage, sensitivity, and precision is planned. Existing catalogs of GALEX sources are incomplete and suffer from a number of artifacts and errors that severely limit our ability to fully utilize these data.

We will reimplement astrometric correction portions of the GALEX mission pipeline and combine those with capabilities available as part of the open-source gPhoton project to entirely recalibrate all GALEX mission direct imaging data, producing new calibrated images with improved astrometric reconstruction for many cases where the original mission's ground calibration pipeline failed. The recalibrated data will be used to construct a photometrically correct, coadd-depth image of the entire UV sky as observed by GALEX. A new photometric extraction pipeline will be developed and deployed to generate a catalog of GALEX ultraviolet sources in both bands at visit and coadd depths, with particular care taken to distinguish extended- from point-sources and improve coregistration across the bands. The resulting extracted photometry will then be screened according to previously developed algorithms to identify unique sources and artifacts. **The GALEX Legacy Catalog (GLCat) will be a high-quality catalog of science-ready UV photometry with improved astrometry, more exposure depth, and higher accuracy and reliability than any GALEX catalog currently available.**

b. **Background.**

i. *The GALEX mission and its legacy.* The Galaxy Evolution Explorer [1] surveyed the sky for over ten years (Apr. '03 - June '13) with a 1.25 degree field-of-view (FOV). Two photon-counting micro-channel plate detectors (MCP) observed simultaneously in bands centered on 1528Å (Far-Ultraviolet or "FUV") and 2271Å (Near Ultraviolet or "NUV") in either imaging or slitless spectroscopic (grism) modes. The maximum contiguous integration or "visit" was limited to 26 minutes (while in Earth's shadow). Nested surveys were performed of different area coverage and depth, most notably the All-sky Imaging Survey (AIS, to FUV=19.9, NUV = 20.8AB mag, covering about 25,000 square degrees of the sky), the Medium-depth sky survey (MIS, depth about 22.7 ABmag in both FUV and NUV, area coverage $\sim$2250 square degrees [2]) and several deep fields that accumulated exposures of tens of thousand of seconds over selected fields (DIS; for example, for 30ksec exposure, reaching 24.8/24.4 ABmag in FUV/NUV). The sky coverage of AIS and MIS is shown in Figure 1, reproduced from [3] and [4], who produced the only catalogs of unique UV sources from the GR6plus7 GALEX data release for AIS and MIS respectively, and remedied or flagged some of the critical flaws in the online data. GALEX also mapped extended nearby galaxies (NGS, e.g., [5]). The final photometric catalogs released during the NASA-funded mission (General Release 7 or "GR7") includes 600M photometric measurements representing 100M unique sources. The most complete science-ready GALEX catalog compiled to date, GUVcat, contains 83M unique sources from AIS only [3].

The resulting discoveries exceeded the initial goals and expectations. These data enabled an unprecedented identification and characterization (e.g. mass, age) of young stellar populations across the extent of nearby galaxies, providing clarifying detail on the star-forming

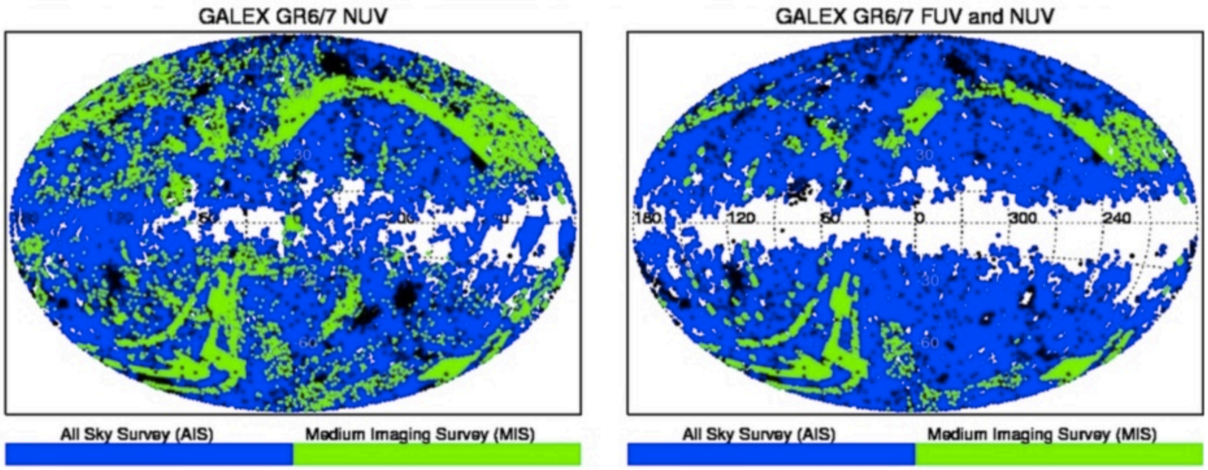

Figure 1. The right-side map shows the sky coverage in both FUV and NUV, i.e. the data included in GUVcat, the best catalog currently available (~83 million unique AIS sources, [3]). There is greatest demand by the community for a unique-UV-source catalog including also NUV-only data (that were discarded by the GUVcat project in order to have FUV and NUV available throughout the sample, according to the authors). The addition of NUV-only data (left panel) will critically extend coverage towards the MW plane, where most hot stars and dust are. Even more equatorial coverage will be gained by re-processing the extended-mission ("CAUSE") data.

process and its temporal and spatial evolution (e.g.,[6],[7], [8], see e.g. [9] for a summary of highlights). Perhaps the most interesting results from GALEX imaging of extended galaxies were unexpected: "extended-UV disks" (XUVD) were discovered in a large fraction of spiral galaxies, i.e. star formation in spiral filaments or clumps stretching out to 4 times the galaxy optical size, where the gas density was believed to have been too low for stars to form (e.g. [10, 11], [12]). UV-bright "rings" were seen around early-type galaxies previously thought to evolve passively (e.g., [13, 14, 15].

The unprecedented UV maps of extended galaxies yielded many early science discoveries, but the extraction and measurement of sources across them continues to pose challenges that the GALEX pipeline was not designed to solve. To analyze extended or compact substructures across the galaxies required ad hoc procedures to be implemented in individual projects (e.g. [6], a methodology then expanded by much subsequent work). Crowding, and underlying flux from the extended objects also hampers measurement of point-like sources within their footprint.

ii. *CAUSE data and Merged Catalogs.* The GALEX mission was extraordinarily productive, effectively squeezing the scientific return of a MIDEX mission into a SMEX budget. Although the FUV detector failed in May 2009, the GALEX spacecraft (with NUV capability intact) survived far past its nominal lifespan, and even past the funding support by NASA. A privately-funded "Complete All-sky UV Survey Extension" (CAUSE) phase followed the mid-2012 withdrawal of NASA support: Caltech continued supporting operations with funds from individuals, groups, and organizations [16].

As shown in Figure 1, during the main mission GALEX did not survey the Milky Way plane, due to bright stars and fields that could potentially damage the detectors. During the

CAUSE phase, several operational safety requirements were relaxed (related to slew rate and field / star brightness limits) to allow targeting of the Galactic plane and a new fast-slew "scan mode" of observation. As will be described in the next section, the ground calibration software was not well-designed for observations with high boresight slew rates, requiring patchwork hack solutions to work at all. Much of the scan mode data is of low quality as a result and has therefore seen little use. Any proprietary periods of privately-funded CAUSE data (many collected in scan mode) have long since expired. **All of the GALEX raw data and mission-produced calibrated and derived products, including for the post-GR7 and CAUSE data, are currently publicly accessible from MAST.** An unfortunate consequence of this unqualified success, and of the unexpected withdrawal of NASA funding while the spacecraft was still functioning well, was a shortage of resources late in the mission to support the production of a legacy-quality data set. The mission team produced visit- and coadd-depth NUV / FUV "merged catalogs" (MCAT) of sources observed up through the last General Release (GR7). These catalogs, now hosted at MAST, were outputs of the mission ground calibration pipeline and intended to serve as operational tools and in service to the primary scientific objective of the mission, "to study star formation in galaxies and its evolution with time." [17, 18] They are not particularly well suited to many common scientific uses without substantial additional effort, as will be described.

iii. *Extant GALEX data products and source catalogs.* Several efforts have been undertaken to generate more science-ready scientific catalogs — all derived from the MCAT — especially to eliminate duplicate measurements of the same source, screen more effectively for data reduction or instrument artifacts, and mitigate source confusion. These catalogs include GCAT ([19], BCScat [4] and GUVcat [3]. GCAT was limited to data up to the penultimate release, GR6, and so is incomplete, and also propagated some issues from the MCAT. GUVcat is currently the best available GALEX catalog for science analysis with AIS data; the authors discovered a number of (previously unreported) wrong co-adds in the standard products, causing biased exposure times, wrong distances from the field center, wrong artifact/rim flagging, etc. GUVcat avoided the bad coadds by using the visit-level data for those fields. The most important added feature in GUVcat was the flagging of sources in the footprint of extended objects such as large galaxies or clusters, where the authors warn that the quality of photometric measurements is severely compromised. The flags allow GUVcat users to filter out these poor-quality measurements, although this also filters out real sources. GUVcat source identification and photometry derives directly from the MCAT; GUVcat added useful warnings but does not solve the core problems with the MCAT, which are enumerated below. **A catalog of unique sources is an indispensable input to research workflows, and a key prerequisite even for something as common as matching to other databases to better characterize classes of astrophysical objects** (e.g., [20, 9]).

iv. *Recent developments in support of this project.* The preexistence of technologies and capabilities developed for two earlier research efforts—gPhoton and GUVcat—significantly reduce the risk and scope of this project.

(1) gPhoton: The original mission pipeline can no longer be made to operate correctly due to a complex dependency environment and "bit rot." gPhoton substantially re-implements key functionality of the GALEX mission calibration pipeline in open-source Python [21]. The gPhoton software accepts raw mission data files, refined aspect solutions, and spacecraft state metadata files to produce calibrated lists of photon events, light curves with requested

sub-visit bin sizes, and images. For the first time, gPhoton has allowed the GALEX data to be used to study astrophysical variability in UV wavelengths on time scales of seconds, including flares [22, 23, 24, 25], white dwarf pulsators [26, 27], and eclipsing binaries [28].

A previously funded and ongoing research project title "Upgrades to the GALEX photon tools [...]" from ADAP16 has further extended the capabilities of gPhoton to include improved image creation, artifact flagging, and a source detection and measurement capability (based on Daophot) for the purpose of mining the GALEX data through GR7 for sub-visit variability [29]. Software has also been developed for this project to simplify bulk reprocessing of data in a cloud processing environment. These software upgrades and scripts have been provided to this team [*pers. comm.*], and serve as a critical jumping off point for the GLCat effort.

(2) GUVcat: This catalog of unique sources is described extensively throughout this proposal. But the GUVcat project has also developed a new cross-matching algorithm to identify unique sources, assign a specific observed source position primacy, and also correctly retain information about secondary source positions. This algorithm not only automates the catalog construction process—which makes it feasible—but makes it fully auditable and reproducible. In addition to drawing significant inspiration from GUVcat, we will rely heavily on this algorithm.

c. **Need for a GALEX Legacy Catalog.**

The GALEX database is the best and most extensive sky survey in the UV so far, and essentially the only one in FUV. Future missions planned or under development will leverage the GALEX UV sky surveys for designing and planning, but none will deliver a better sky survey. **There is tremendous need for a true legacy UV database, including all existing GALEX data, corrected for the known flaws of the MCAT photometric catalogs, and achieving a superior, homogeneous quality of source extraction and calibration.** The GALEX Legacy catalog, GLcat, will be a unique UV-source catalog, but each source will also contain time-domain information from all existing repeated observations of the same source. GLcat will enable selection of source samples, matching with other databases or with known samples, finding all GALEX measurements of a given object, or selecting and studying entire populations of object classes in the UV (e.g., hot stars, redshift < 2.5 QSOs, star-forming galaxies, ...), as well as support tuning of science drivers and instrument specs for planning future missions and instruments.

c.1. GLcat will be the first catalog of UV sources from the entire GALEX database: Inclusion of NUV-only, non-AIS, post-GR7, and CAUSE data.

The science-ready catalogs of unique GALEX sources that have previously been produced contain only a fraction of the available GALEX data. There is not a catalog of unique GALEX sources that includes all data through GR7. The catalog of Kepler field data produced by [30] is the only science-ready catalog that includes any data from the CAUSE phase. **GLCat will be the first catalog of unique sources from the entire GALEX mission.** The CAUSE data contain about 1750 eclipses of NUV observations, or as much as 2.8 million seconds of new exposure time, most of regions of the sky not covered at all prior to GR7.

However, CAUSE data has (as yet) uncorrectable photometric problems. Bright sources and fields induce non-linear response in the GALEX detectors due to both temporary localized depletion of charge from the electron multiplier plates and global dead time effects due to event readout. [31] estimated a 10% rolloff in sensitivity for point sources with ABmag of ∼13.8 in both bands. Time-domain analysis of bright sources with gPhoton has revealed that the effects are much more complex than a simple rolloff in response or saturation effect [32]. And the problem is uncharacterized and entirely unsolved for dense fields of bright sources like the Magellanic Clouds or Galactic plane (e.g.,[33, 34]). It is also possible that the relaxation of bright star / field limits caused local or global degradation of the detectors. The sources from these fields will appear in GLCat, but their photometric information will be flagged as unreliable. We hope that these data can be photometrically calibrated at some point in the future, but it is outside the scope of this project. Our team includes an unfunded collaborator with significant prior experience with CAUSE phase data, who will advise us on how to maximize their utility with existing capabilities.

c.2 GLcat will improve image reconstruction and source extraction: Aspect solution problems and missing exposure time for petal-pattern and scan modes

To avoid detector burn-in and gain sag effects, GALEX did not maintain a fixed pointing during observations, but drifted slightly in pre-set patterns. The photon-counting nature of the detectors was then leveraged in ground processing to correct for this effect to generate high-quality images. Four main classes of observing patterns were used by the mission. The first, and most common, was the All-sky Survey (AIS) pattern in which 10 separate and distinct positions on the sky were observed for 100s each (a "leg") during a 1600 eclipse, with the detectors placed in a non-observing state as the spacecraft slewed from one region to another. The Medium Imaging Survey (MIS) mode observed the same 1.5 degree cone of sky with a tight spiral "dither" pattern for the full eclipse. A "petal-pattern" mode observed a slightly large cone of sky by tracing out a spirograph-like shape with 8-12 legs (or petals) over an entire eclipse. In a fourth pattern, the "scan mode" described above, long strips of sky were observed in a "down and back" pattern. Other GALEX programs, such as the Deep Imaging Survey or Guest Investigator programs, used combinations of these modes. A fifth observing pattern for calibration observations, "CAI", was a hybrid between AIS and petal-pattern. In the calibration pipeline, the spacecraft attitude and control system (ACS) "aspect solution" was used to generate 1-second images which were matched against known guide stars to create an intermediate correction to errors in the ACS. The intermediate solution was used to generate 100-second images which were matched to the ACT [35] and USNO-A [36] star catalogs to generate a final refined aspect solution. The refined aspect solution was then used to generate "science-ready" images with astrometric precision yielding source position accuracy of 0.35/0.48″ (NUV/FUV) in GR6 and 0.32/0.34″ (NUV/FUV) in GR7. This approach had two major failure modes, which this project will correct.

(1) Aspect refinement failure under high slew rates: The aspect refinement consistently failed when the slew rate was high. In particular, large fractions of exposure in petal-pattern (typically ∼25%) was lost due to a failed aspect solution. The petal-pattern mode was often used to safely observe regions of the sky with very bright sources for GALEX (up to ∼9 AB mag in NUV), sources that more likely overlap with the detection limits of many of the modern all-sky surveys in other bands. The issue was much worse for scan mode observations, with the result that investigators have been forced to simply discount large amounts of the total observing time of regions of sky of tremendous scientific interest.

We estimate that about 30% of scan mode exposure time is of low quality due to aspect refinement issues, and there were about 1200 petal-pattern style observations made through

GR7, of which typically 25% of the exposure time is "lost" to high slew rates. We therefore estimate that **the implementation of a new aspect refinement stage will lead to the recovery of about 1.3 million seconds of exposure time**, 480ks of which was not previously available in *any* form.

(2) Imprecise revisit astrometry: Separate observations of the same region of sky are often slightly offset. Although seemingly a minor issue, this can frustrate and complicate attempts to produce high-quality coadded images, analyze the same source across multiple visits, and produce catalogs of unique sources. GLCat will improve revisit astrometry by using prior visits as inputs to aspect refinement.

c.3. GLcat will correct distortions and FUV-NUV mis-alignments

The NUV and FUV detectors were not perfectly aligned, and their alignment was not constant in time. The mission calibration pipeline included a correction for this effect in the form of an eclipse-dependent (x,y) offset to the FUV band images. However, the effective sizes and shapes of the detectors also vary over time (mostly as a function of temperature). The effect is small, but can complicate the problem of accurately cross-matching across bands. The mission team knew about the problem, but couldn't find a solution that was possible with their available resources; all approaches would have required a substantial rewrite of the ground calibration software, which is an effort this project can now undertake. **This project will improve the GALEX astrometry by anchoring the image geometry to the Gaia catalog, with corrections for second-order distortion effects in both bands.**

c.4 GLcat will have consistent FUV and NUV source measurements

Figure 2a is a GALEX image of NGC 300 with overlaid apertures of MCAT detected sources. Note that the main disk of the galaxy was detected as 1-3 extended sources despite containing clear point sources. At the outer edges, point sources and small extended sources are detected accurately. The same issue is further demonstrated in Figure 3, wherein NUV band detects large number of sources at the periphery of the cluster NGC6218 and none in the core, an obviously wrong result; the NUV / FUV merging then generates in a dramatic undercount of dual-band sources. This issue arose in part because the source detection portion of the GALEX mission pipeline was implemented as a compromise between detection of extended and point sources by tuning the DEBLEND_MINCOUNT parameter in Source Extractor [37].

Figure 2b is a GALEX observation of sparse cluster NGC 2420 overlaid with source detections from the MCAT (pink) and a custom photometry pipeline developed by [5] based on Daophot (green) [38]. Note that several clusters of distinct point sources are treated as a single extended source by the MCAT but correctly identified by Daophot.

This problem was pointed out by [3], with a clear warning to not use pipeline measurements for sources within the footprint of extended objects (with flags provided to identify such cases), however the incorrect measurements were nonetheless propagated to GUVcat from the MCAT visit- and coadd- level photometry on which it was based. GUVcat provides flags to sieve out these flawed measurements. **GLCat will mitigate the confusion of extended and point sources by running source detection and extraction twice, optimized for both extended and point sources.** The basic methodology has already been created but requires refinement: use Daophot for point sources and Source Extractor for

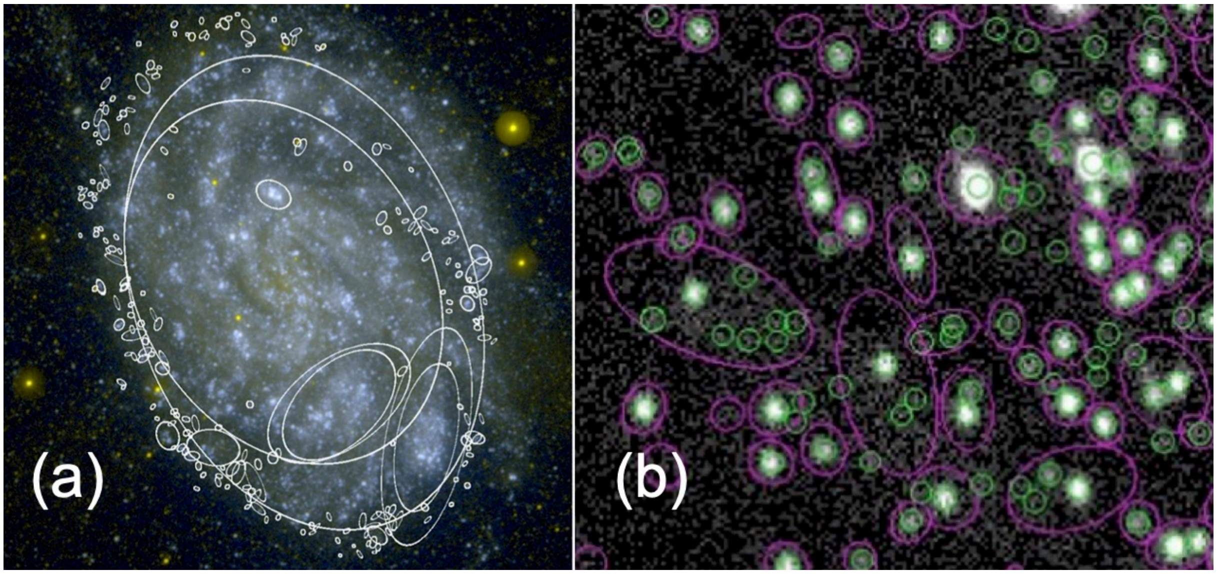

Figure 2. (a) The nearby galaxy NGC300 in a composite GALEX image (blue=FUV, yellow=NUV). Superimposed are contours of NUV sources measured by the MCAT pipeline. Note common source blending and confusion. (b) A subsection of the sparse cluster NGC2420. Pink contours delineate MCAT sources. Note several cases where two or more well resolved point sources are combined into one extended source. This problem is common in the MCAT and flagged but not corrected in GUVcat.

extended sources. GFCat [*pers. comm*] and [5] have demonstrated that Daophot produces extremely good completeness for point sources. For extended sources, testing has confirmed that setting the DEBLEND_MINCOUNT parameter in Source Extractor to higher values resulted in more accurate identification of extended objects [37]. FUV and NUV sources will be matched and measured consistently. **To generate a catalog that includes correct, consistent measurements for every source—and remedies other flaws—requires complete reprocessing of the data with better reconstruction, reliable source identification, and simultaneous cross-band measurements.**

c.5. GLcat will correctly merge multiple observations

Some of the extended sources in Figure 2a also have multiple overlapping detections because the center coordinates of detections on different visits were far enough apart that even the careful screening for GUVcat failed to distinguish them. This is also a common problem for extended sources in the MCAT. **GLCat will eliminate duplicate detections of extended sources by running source detection and extraction on full-depth coadded images, in addition to the visit-level images.** By construction, there can only be a unique detection of an extended source in a single coadd image.

c.6. Non-observation *vs* Non-detection.

Most but not all observations were collected with both bands while both detectors were functioning. And about 90% of sources detected in the NUV band have no matching detection in the FUV [3]. Because the MCAT performed source detection separately in each band, it is difficult to determine whether the absence of an entry matching any particular source position in one or both bands represents a non-detection of the source or a non-observation; In the case of true non-detections, it is similarly difficult to determine the level of background at the particular location in the particular band, which is needed to establish the significance of the non-detection or an upper limit. This confusion severely hampers efforts to perform statistical analyses with GALEX catalogs, and led the authors of GUVcat to include only observations with both detectors exposed, to circumvent the problem.

Figure 3 provides an example of the issue. A large number of sources in this observation of NGC6218 are clearly present in both bands while only having been detected in one. The MCAT assigns the same flag value to the non-detection as if the source had not been observed at all, and does not provide a corresponding flux measurement in the "non-detection" band in order to establish the significance or detection threshold.

gPhoton [21] partly solves this problem with the gFind tool that reports the GALEX exposure times of any requested point on the sky by determining when and if the position falls within a detector radius of the boresight, using a database of the refined aspect solutions up to GR7. However, the combination of database and web response times makes this option too slow to be tolerable for more than a few thousand sky positions. **GLCat will be produced by performing identical source detection in each band individually and photometric extraction in both bands identically, solving the problem of characterizing non-detections in either band.**

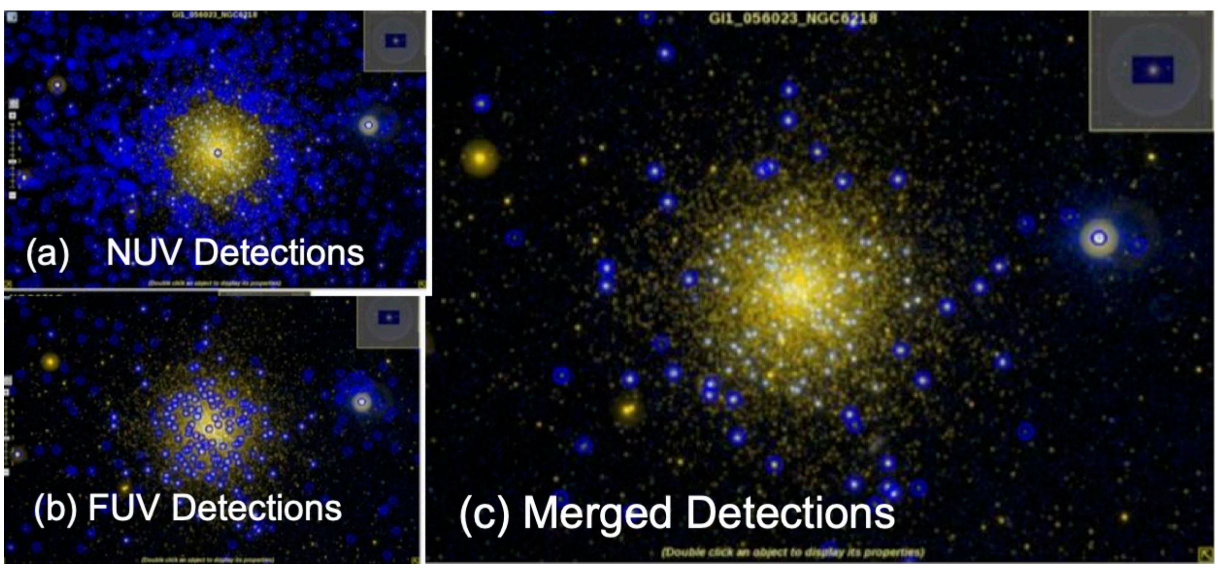

Figure 3. NGC6218 is a crowded cluster in NUV, with sparse FUV-emitting sources. MCAT source detection locations (not extents) are marked with blue circles. (a) The MCAT pipeline treats the core of the cluster as a single extended object but detects many point sources at the periphery. (b) In FUV, it is the opposite; the MCAT detects a large number of point sources in the core. (c) The result of merging the bands is that only a few sources are matched between FUV and NUV, and they are measured over inconsistent integration areas. GLCat will solve this problem by running source detection and extraction twice, with optimizations for point and extended sources respectively in both bands. GLCat will also perform identical source extraction (i.e. from the same source position and aperture lists) in both bands; this has the additional benefit of establishing the significance of non-detections in either band.

c.7 Bad co-adds of separate visits
The work of [3] found that a fraction of GALEX coadd images (640 coadds from 1195 visits) of dual-band AIS observations were constructed with visit-level data with incorrect World Coordinate System (WCS) information. The result was incorrect exposure times, flags, and distance from field center, causing some sources that should have been excluded to intrude previous catalogs, and loss of sources that would meet the criteria. GUVcat replaced bad coadd-depth observations with good visit-depth observations. **GLCat will be able to address the problem by correcting the WCS information for "bad" visits.**

c.8 A unique-source list, and time-resolved information, in one legacy catalog
The current GALEX database (MCAT) includes repeated measurements of sources from re-observations or field overlaps. While these are useful for serendipitous variability searches (e.g., [**?**] and references therein), a list of unique sources is needed to extract and study selected samples, and to match databases at other wavelengths (e.g. [20, 9]). In response to this need, GUVcat and its precursors were created by the community. GLCat will be a list of unique sources, more complete and with improved matching between repeated observations, and between FUV and NUV. But for sources found in multiple visits, tags will also indicate the number of repeats, dates, exposure times, and magnitudes. **This will make GLCat incredibly versatile: it can be used as the primary reference list of unique GALEX UV sources, and it can be used for mining the serendipitous time-domain information included in >ten years of GALEX data.**

d. **Broad Significance. Impact and Lasting Value of the GALEX Legacy Catalog.** As already noted, existing GALEX source catalogs are incomplete and carry along problems from the original mission pipeline. GLcat will contain information from the entire GALEX database ($\sim 54,000$ eclipses), entirely reprocessed to improve image reconstruction, registration, source extraction and calibration, as well as adding significant new exposure time and spatial coverage over previous GALEX catalogs. It will contain science tags, artifact flags, and time-domain information. As the name suggests, GLCat will be the legacy reference of the GALEX mission, for which no comparable mission is planned. Examples of science applications, of interest to us or to others, include a comprehensive census and characterization of hot WDs (elusive at all wavelengths except the UV), to clarify late stages of stellar evolution driving the chemical yield, ionized nebulae, QSOs out to redshift $\sim$2.5, and star-forming galaxies. Given the sensitivity of UV fluxes to even small amounts of dust, 3D dust maps in the Milky Way can be derived by combining GLCat with Gaia's distances.

GLCat will enable cross-matching with surveys at other wavelengths to classify sources and identify peculiar classes of objects, as well as identifying counterparts of X-ray sources and interesting objects discovered at other wavelengths. GLCat will be a roadmap supporting design of future UV instrumentation and new observations with existing telescopes. GALEX data are already being used, with difficulty, for planning and design purposes by the NASA-funded SPARCS ultraviolet cubesat space telescope [39] and the Weizmann Institute's ULTRASAT ultraviolet survey mission [40]. Note, however, that neither of these missions will be capable of achieving anything close to the spatial coverage, spatial and temporal resolution, and photometric depth of GALEX. While successive series of sky surveys with progressively higher quality have been and will be performed at shorter and longer wavelengths, to our knowledge there are no plans for a better ultraviolet sky survey than

GALEX. It is the best UV dataset with nearly all-sky coverage, but the wealth is currently difficult to mine. **GLCat will enable the maximum science return from GALEX.**

e. **Plan of Work.** Tasks are listed in a logical order, not as a timeline. All tasks are necessarily interrelated, but some rely on others to be partially or mostly completed before they can start, whereas other tasks can be completed in parallel. A Gantt chart summarizing the distribution of work effort across time and tasks appears as Figure 4. See the section titled "Project Estimation" below for a summary of how the work plan and time / budget estimates were generated.

i. *Task 1: Implement a new aspect refinement approach for the GALEX mission.* As described above, the mission ground calibration pipeline performed aspect refinement by matching 1-second depth images to a catalog of known, bright guide stars. The offset between the spacecraft ACS output (which had a resolution of 1-second) and the match position was used as a correction. The refined aspect solution was then used (with interpolation) to re-project photon events on the sky to generate a final image. This approach to aspect-refinement failed frequently during rapid-slew maneuvers such as petal-pattern and scan mode, likely because the point sources in even short images were smeared enough to make matching difficult. We will implement a new aspect refinement pipeline that uses a "shift-and-add" coregistration approach to correct the data against itself and also against other observations of the same region of sky. The exact choice of co-registration algorithm is an open question to be addressed as part of our work plan. A large number of options exist, including "drizzle," Fourier coregistration, and various Maximum Likelihood (ML) approaches. Single-second images for many GALEX fields will be photon-limited, as well, which adds an additional consideration. We think it may also be useful to leverage additional cycles of refinement by, e.g., integrating / refining at longer image depths (e.g. 10-seconds) on a first pass. We will derive World Coordinate System (WCS) information by cross-matching to Gaia, given the approximately correct initial WCS guess that can be derived from the raw aspect solution data. The dual-band coregistration will also make use of a crossmatch, and include parameters for possible second order distortions in the detector (i.e. scale and skew) which will be looped back in as an input to the image generation process to create the final calibrated images.

At each stage, data quality will be assessed visually and also by matching sources (extracted by an early version of the source extraction pipeline described below) to existing catalogs, including the MCAT. This is a substantial effort, equivalent to re-implementing about half of the calibration pipeline of a major survey mission with an almost entirely different methodology. It is, however, feasible because the open source gPhoton s/w has already implemented the other half. The return on this effort will also be substantial. We have allocated 0.84 FTE to this task which will span the first half of the project period. This includes 0.52 FTE for the algorithm development and reprocessing for the refined aspect solutions, 0.14 FTE for the algorithm development and reprocessing of assigning WCS information, and 0.18 FTE for the revised cross-matching of the NUV / FUV bands.

ii. *Task 2: Regenerate calibrated data for the entire GALEX mission.* Having generated new refined aspect solutions for the entire mission, we will use those to regenerate calibrated image data. The technical problems associated with this task are already almost completely solved by gPhoton. Briefly, the ‘gPhoton.PhotonPipe‘ function is provided with a raw observation data file, a "spacecraft state" metadata file, and a refined aspect solution file, and it conducts all necessary detector-space calibrations including aspect-correction of individual photons, flat-fielding, and flagging for certain categories of detector anomaly (like hotspot and edge effects), outputting a list of calibrated photon events. A separate function is then called to convert the calibrated photon events to a calibrated image with 1.5" resolution, proper WCS header information, and calibrated effective exposure time. We will additionally implement propagation of flags from the mission planning database and quality-assurance output to the headers of these images, which will allow for the screening of observations with known (and unrecoverable) low quality due to spacecraft anomalies. We have allocated 0.175 FTE to this task, largely in YR2, to include flag propagation, developing production scripts, managing reprocessing, and validation / QA.

iii. *Task 3: Create a calibrated full-depth coadd image of the entire GALEX mission.* The improved calibrated images and diffuse "background" sky images (described below) will be used to create two corresponding coadd-depth mosaics of nearly the entire UV sky. In addition to simply being neat, these **full-sky coadds will serve as easy references for the "best available" calibrated GALEX imaging data.** While not technically difficult, this task involves a large component of "bookkeeping" and quality-assurance, including manual review of data. It will be lead by the Programmer; a total 0.26 FTE has been allocated.

iv. *Task 4: Re-implement the sky background estimation algorithm for the GALEX mission.* The sky background calculation employed an iterative sigma-clipping and interpolation approach to convert GALEX images to "sky background" images. The "sigma-clipping" algorithm was modified to take advantage of the full Poisson distribution because of the very low background countrates in GALEX. We have allocated 0.2 FTE to the task, split between code development in YR1 (in parallel to source extraction and aspect refinement tasks) and data processing and validation (following image data reprocessing). Code development can be done using mission-produced images as inputs, whereas reprocessing of sky background images will require the new calibrated image data.

v. *Task 5: Implement a new source detection and photometric extraction procedure.* The mission calibration pipeline made use of the Source Extractor [41] software package for source detection and photometric extraction, modified to make use of the custom sky background images when propagating photometric errors. This approach produced the problems described above, causing confusion between the classification of point and extended sources. Work by [5] and [29] used the Daophot tool with much more success distinguishing point sources. Because SE has improved capability to detect extended and elliptical sources over Daophot, we intend to use both tools for what they are best for. We will implement one version of source detection / extraction that uses SE, based on the mission pipeline approach, optimized to find and measure extended options, and an additional implementation of Daophot that uses Daophot optimized to find and measure point sources. We have allocated 0.28 FTE to this task in YR1; it can take place in parallel to the aspect refinement and sky background tasks because we will be able to use mission-produced images for testing and development. Source extraction will be conducted on the recalibrated images at the end of YR3. The reliability of the photometric extraction is absolutely critical to the production of a high-quality GLCat, so we have allocated 0.3 FTE in YR3 to the validation and quality assurance of photometric measurements. We will validate the data by rapid visual inspection of images with overplotted photometry for *every* GALEX observation to confirm expected behavior and by systematic comparisons against the MCAT and GUVcat (e.g. with direct matching of source positions, histograms of photometry, bulk source counts, etc.) with follow up on the nature of any discrepancies (which may be *improvements*).

vi. *Task 6: Crossmatch the NUV / FUV bands to create a new merged catalog.* We will crossmatch dual-band sources following the methodology of [3]. The results will be more stable thanks to GLCat improved image reconstruction and alignment. We have allocated 0.15 FTE to the effort, split between implementation and validation, at the end of YR2 and beginning of YR3, with development preceding and processing roughly in parallel with the source extraction effort. This task relies on output from source extraction, but it does not need to be completed before dual-band crossmatching can begin.

vii. *Task 7: Preparation and delivery of catalogs to MAST and SIMBAD VizieRCatalogs.* The GALEX Legacy Catalog will be provided to the Mikulski Archive at Space Telescope (MAST) as a High Level Science Product (HLSP), as well as to the Casjobs database, and to SIMBAD VizieR near the end of the project, for ease of queries and cross-matching with VO tools. The task will be led by a Co-I with previous experience in both of these activities. A total of 0.1 FTE has been allocated.

viii. *Task 8: Preparation and publication of peer-reviewed journal articles.* We have allocated 0.1 FTE each for the preparation of two peer-reviewed publications as part of this project. All project participants who have contributed significantly to the work will participate in paper preparation, with the PI leading. The first paper, expected in the second year of the project, will provide a description of technical solutions developed for the aspect refinement, sky background, and source detection / photometric extraction developed in the first year of the project. We plan to submit this paper to the journal Astronomy Computing. The second paper will be a high level description of the GALEX Legacy Catalog, to serve as the primary reference for users of this product. We expect to submit it (to Astrophys. J. Suppl.) late in the third year, approximately timed with the availability of GLCat at MAST and SIMBAD.

ix. *Task 9: Disseminate and communicate results at professional conferences.* The PI will attend two conferences to disseminate intermediate project results. The first conference planned is the Astronomical Data Analysis and Software Systems (ADASS) conference to be held in South Africa in Nov 2021, where initial results from the aspect refinement, source extraction, and background estimation tasks will be presented. The second conference will be the American Astronomical Society (AAS) winter meeting (#243) to be held in Jan 2024 in New Orleans where the PI will present a description of the GLCat in anticipation of its imminent release. Each conference is 1 week and therefore allotted 0.025 FTE; an additional 0.025 FTE is allocated to prepare the ADASS proceedings contribution.

x. *Project Estimation Methodology.* To assess project feasibility and requirements, we used a project estimation approach that we have adapted from commercial practice and modified to be more appropriate for the high-uncertainty environment of cutting edge research. We broke the project down into major tasks and then subtasks as needed to reach a granularity where every well-defined unit of the project had a scope that we could conceive of accomplishing. We then estimated the level of effort (LoE) required for each subtask. Initial estimates were based on our prior experience doing similar work. We then assigned an "uncertainty" scale factor of greater than 1 to each estimate as a rough measure of how confident we were in our initial estimate. For example, a situation in which we planned to identically recreate work

Task Number	Task Description	Task Owner*	FTE Est.	Year 1 (04/01/21 - 03/30/22)						Year 2 (04/01/22 - 03/30/23)						Year 3 (04/01/23 - 03/30/24)					
				Apr-May	June - July	Aug-Sept	Oct-Nov	Dec-Jan	Feb-Mar	Apr-May	June - July	Aug-Sept	Oct-Nov	Dec-Jan	Feb-Mar	Apr-May	June - July	Aug-Sept	Oct-Nov	Dec-Jan	Feb-Mar
1	Refine aspect	PI	0.840	0.050	0.050	0.070	0.070	0.070	0.130	0.130	0.070	0.055	0.040	0.040	0.065	0.000	0.000	0.000	0.000	0.000	0.000
1.1	Implement self-coregistration		0.520	0.050	0.050	0.070	0.070	0.070	0.130	0.080											
1.1.1	Develop approach		0.300	0.050	0.050	0.050	0.050	0.050	0.050												
1.1.2	Process data		0.060			0.020	0.020	0.020													
1.1.3	Validate and QA		0.160						0.080	0.080											
1.2	Derive WCS		0.140								0.040	0.030	0.015	0.015	0.040						
1.2.1	Prototype		0.040								0.040										
1.2.2	Production code		0.030									0.030									
1.2.3	Manage processing		0.030										0.015	0.015							
1.2.4	Validate and QA		0.040												0.040						
1.3	Crossmatch bands	CI	0.180							0.050	0.030	0.025	0.025	0.025	0.025						
1.3.1	Prototype		0.050							0.050											
1.3.2	Production code		0.030								0.030										
1.3.3	Manage processing		0.050									0.025	0.025								
1.3.4	Validate and QA		0.050											0.025	0.025						
2	Reprocessing	P	0.175					0.050		0.050	0.017	0.017	0.017	0.025							
2.1	Manage flag propagation		0.050					0.050													
2.2	Production code		0.050							0.050											
2.3	Manage processing		0.050								0.017	0.017	0.017								
2.4	Validate and QA		0.025											0.025							
3	All sky coadd	P	0.260												0.040	0.040	0.060	0.030	0.060	0.030	
3.1	Prototype		0.080												0.04	0.040					
3.2	Production code		0.060														0.060				
3.3	Process data		0.060															0.030	0.030		
3.4	Validate and QA		0.060																0.03	0.030	
4	Sky background	P	0.200	0.040	0.040	0.020	0.020						0.020	0.020	0.040						
4.1	Prototype		0.080	0.040	0.040																
4.2	Production code		0.040			0.020	0.020														
4.3	Process data		0.040										0.020	0.020							
4.4	Validate and QA		0.040												0.040						
5	Source extraction	PI	0.660	0.070	0.070	0.070	0.070						0.027	0.027	0.027	0.100	0.100	0.100			
5.1	Prototype		0.140	0.070	0.070																
5.2	Production code		0.140			0.070	0.070														
5.3	Process data		0.080										0.027	0.027	0.027						
5.4	Validate and QA		0.300													0.100	0.100	0.100			
6	Merge bands	PI / CI	0.150												0.025	0.050	0.050	0.025			
7	Deliver catalogs	CI / PI	0.100																0.025	0.050	0.025
7.1	MAST		0.050																0.025	0.025	
7.2	SIMBAD		0.050																	0.025	0.025
8	Write papers	PI	0.200								0.050	0.050							0.050	0.050	
8.1	Paper #1		0.100								0.050	0.050									
8.2	Paper #2		0.100																0.050	0.050	
9	Conferences	PI	0.075				0.025	0.025											0.025		
9.1	ADASS XXXI		0.050				0.025	0.025													
9.3	AAS243		0.025																0.025		
Total			2.660	0.160	0.160	0.160	0.185	0.145	0.130	0.180	0.137	0.122	0.103	0.112	0.197	0.190	0.210	0.155	0.160	0.130	0.025

Figure 4. Gantt chart showing distribution of effort across time and tasks. Task leader key: PI=PI, CI=Co-I, P=Programmer.

that we'd done previously would be considered very accurate and assigned a scale factor of one. A situation in which our initial estimate was only a guess, perhaps because it was in a domain with which we had little experience, might be assigned an uncertainty factor of 3 or more. Given our extensive prior experience with projects of this type, none of our scale factors were greater than 2. The PI and Co-I iterated on and agreed upon LoE and scale factors before proceeding. The sum of the initial estimates forms the lower bound on the estimate: the LoE required in the case where the project proceeds exactly according to our expectations. The sum of initial estimates multiplied by their uncertainty factors forms the upper bound of our estimate: the LoE necessary to guarantee project success. We ran the estimation exercise twice. In the second round, some of the subtasks were refactored based on discussions about methodology and technical approach. We did not reference the first estimate during the second, but both returned similar results (within 0.1 FTE): 1.5 FTE is the minimum required effort for this project, and 2.5 FTE is necessary to guarantee project success. We are requesting support for 2.66 FTE, which includes 0.3 FTE of a TBD undergraduate intern from a nearby university who we expect to work at lower efficiency than the professional-level programmers (of approximately our own abilities) assumed during the estimation exercise. We are confident, therefore, that **the requested level of support is both reasonable and sufficient to complete the proposed project.**

xi. *Cloud Processing Allocations.* We have budgeted for the provisioning of Amazon Web Services (AWS) cloud-based instances and storage for the major reprocessing tasks proposed under this work. Although we are aware that NASA High Performance Compute (HPC) resources are potentially available, and this project team also has access to similar compute clusters through institutional affiliations, these systems are not appropriate for the work planned. First, although highly parallelizable, the processing that we propose to do is not primarily CPU-limited. The major limitations are hard disk size and virtual memory, which need to be scalable to our task and available on demand throughout the project. HPCs do not typically permit the local storage of many hundreds of terabytes of data for several years, nor permit the allocation of 100Gb of virtual memory per task, which is what we will require. Furthermore, this team has prior experience developing and deploying data processing applications on AWS and high performance compute clusters, and our experience is that the administrative barrier that must be put in place on shared HPC resources for security reasons lead to a tremendous loss of efficiency for developing and testing software of this type. The gPhoton code has already been developed and deployed on AWS for the GFCat project. [*pers. comm.*] So the use of AWS maximizes our ability to guarantee success of this project.

Costs for cloud resources are notoriously difficult to prefigure. Our primary concern is having too little compute resources available. Our estimates are based on the recent experience of the GFCat project in reprocessing all MIS data through GR7 on AWS. [*pers. comm.*] We have scaled their approximate compute costs for reprocessing by $\sim$2.5 to account for the additional data volume of AIS and scan mode, and multiplied that by the number of times that our work plan calls for *some version* of a "complete reprocessing" (which is 8). We expect many of the reprocessing steps to be less computationally expensive than the GFCat baseline (such as source extraction, which was only a subset of GFCat processing), but others to be more so (particularly aspect refinement); we think that treating the baseline as the average is therefore reasonable. Then we approximately doubled that number to include a margin up to and including a need to completely reprocess at any stage.

f. **Data Management Plan.** This project team is committed to open and reproducible research. It is our intention that all of our scientific data products and results can be fully reproduced from publicly available source code and documentation with minimal effort. **Any data and source code underlying figures, tables, or other results in publications or archived work products will be provided / included as supplementary material or documentation.**

i. *Resulting Products.* **The primary data product of this effort will be a catalog of unique UV sources at both the visit and coadd level from the entire GALEX mission.** The MCAT data through GR7 contains 600M sources at the visit level. We estimate that our final catalog database will contain 1B rows / sources — including both visit and coadd level data, and flagging to identify unique sources — and approximately 50 columns for each source. The database will be hosted at the Mikulski Archive for Space Telescopes (MAST) as a high-level science product (HLSP), and ingested into MAST Casjobs and Simbad/Vizier at no cost to this project (per the provided letter of commitment).

This project will also produce calibrated sky and "sky background" FITS images, new refined aspect solution files, and "quicklook" jpeg images. We estimate the compressed data volume to about about 3Mb per GALEX eclipse, or <200Gb for 54,000 eclipses. **The project will also produce coadd-depth images of the entire UV sky and diffuse UV sky** , as observed by GALEX, delivered as tiled FITS images; we estimate the compressed data volume to be <200Gb for each.

This project will also generate a number of software libraries and tools. The major software products to be developed will include (1) a new aspect-refinement pipeline for GALEX data, including assignment of WCS metadata, (2) scripts and other software to aid in GALEX reprocessing, including flag propagation from the mission planning system files, (3) scripts for the production of all-sky coadd images, (4) a reimplemented background-estimation algorithm for GALEX data, (5) one or more source extraction / measurement pipelines optimized for point and extended sources in GALEX data, (6) tools and scripts for cross-matching of GALEX point sources across and within bands, and for the identification and flagging of unique sources, (7) scripts for the construction of a catalog of unique sources at visit and coadd depths.

The primary development language will be Python. **Software and source code developed as part of this project will be publicly released under a permissive open-source license**, and we will strongly favor the use of open-source tools and software dependencies. Source code will be hosted on the PI's institutional webpage or version control repository (e.g. Github), and will be included as "documentation" along with the HLSP catalog delivery to MAST. Archived source code will include information about the operating environment in which the code was developed and run, including OS and other dependencies, to aid reproducibility. The PI will retain virtual machine images within examples of any running source code, with all dependencies, necessary to reproduce major data products or results of this effort in non-public institutional digital repositories.

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