THE SECOND GALAXY ULTRAVIOLET VARIABILITY (GUVV-2) CATALOG

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ABSTRACT

We present the second Galaxy Evolution Explorer (GALEX) Ultraviolet Variability (GUVV-2) Catalog, which contains information on 410 newly discovered time-variable sources gained through simultaneous near UV (NUV 1750–2750 Å) and far-UV (FUV 1350–1750 Å) photometric observations. Source variability was determined by comparing the NUV and/or FUV fluxes derived from orbital exposures recorded during a series of multiple observational visits to 169 GALEX fields on the sky. These sources, which were contained within a sky area of 161 deg², varied on average by ΔNUV = 0.6 mag and ΔFUV = 0.9 mag during these observations. Of the 114 variable sources in the catalog with previously known identifications, ∼67% can be categorized as being active galaxies (quasar stellar objects (QSOs), Seyfert 1, or BL Lac objects). The next largest groups of UV variables are RR Lyrae stars, X-ray sources, and novae. By using a combination of UV and visible color–color plots we have been able to tentatively identify 36 possible RR Lyrae- and/or δ Scuti-type stars, as well as 35 probable active galactic nuclei (AGNs), many of which may be previously unidentified QSOs or blazars. Finally, we show data for three particular variable objects: the contact binary system of Sloan Digital Sky Survey (SDSS) J141818.97+525006.7, the eclipsing dwarf nova system of IY UMa and the highly variable unidentified source SDSS J104325.06+563258.1.

Key words: galaxies: active – stars: variables: other – ultraviolet: general

Online-only material: machine-readable and VO tables

1. INTRODUCTION

The NASA Galaxy Evolution Explorer (GALEX) satellite, launched on 2003 April 28, is currently making imaging photometric observations of the sky in two ultraviolet bands (NUV 1750–2750 Å, FUV 1350–1750 Å). A summary of the main scientific findings obtained during the first year of its on-orbit operation can be found in Martin et al. (2005) and references therein. Repeated (i.e. multi-orbit) observations of selected areas of the sky are made in the Deep Imaging Survey (DIS) (Morrissey et al. 2005, 2007) and in certain Guest Investigator (GI) observations. This observing strategy requires making repeated visits to the same position on the sky with the 1.2° instrument field of view, thus enabling numerous astronomical sources to have their FUV and NUV fluxes to be determined at many different epochs. From these observations it is thus possible to detect variable ultraviolet sources, many of which exhibit much larger amplitudes of variation in the ultraviolet region than that typically found at visible wavelengths. A list of 84 time-variable UV sources discovered during the first 14 months of the GALEX mission (i.e., 2003 June–2004 August) has been presented by Welsh et al. (2005) in version 1.0 of the GALEX Ultraviolet Variability (GUVV) Catalog. The great majority of these 84 UV variable objects were found to be either RR Lyrae or dMe flare stars, together with a few Delta Scuti and X-ray variable sources. Since the publication of the first GUVV catalog several papers have been published on the more extreme cases of UV source variability, such as the GALEX high time-resolution (<1 s) observations of flares on four nearby dMe stars (Welsh et al. 2006) and the large-amplitude UV variations found for the RR Lyrae star ROTSE-I J143753.84+345924.8 (Wheatley et al. 2005). We note that the observation of flux variability in astronomical objects can provide important constraints on the physical processes responsible for the observed emission, especially in the cases of X-ray/UV emission from highly energetic sources such as active galactic nucleus (AGN) and black hole candidates.

In this paper we report on the analysis of new GALEX observations of 169 sky fields performed during the 2003 June–2006 June time frame. Each sky field was observed at least 10 times, each for a period of 1200 s–1700 s. We report on 410 newly discovered UV variable sources which will subsequently require follow-up observations in other wavelength bands in order to fully describe the true physical nature associated with the variability of each of the listed sources.

2. OBSERVATIONS AND DATA ANALYSIS

We have used the GALEX FUV and NUV-band photometric data catalogs compiled during the period 2003 June–2006 June, which reside in the Multi-Mission Archive at the Space Telescope Science Institute (MAST). Only the GALEX fields observed on ten or more occasions (and with exposures of more than 200 s) were included in our present analysis. A list of each sky field, together with the number of separate observations (or “exposures”), is given in Table 1 and the distribution of these fields on the sky is shown in Figure 1. Since the prime scientific reason for selecting these fields was to carry out GALEX UV observations of galaxies and/or galaxy clusters, it is not surprising that the vast majority of these sky fields are located away from the galactic plane such that saturation of the detectors due to overly-bright stellar sources and the effects of interstellar absorption in the galactic plane are both minimized.

The data files for each exposure of the 169 1.2° diameter sky fields contain photon events that have been processed using the standard GALEX Data Analysis Pipeline operated at the Caltech Science Operations Center (Pasadena, CA). This pipeline ingests time-tagged photon lists, instrument and spacecraft housekeeping data, and satellite pointing aspect information (Morrissey et al. 2007). The data pipeline then
uses a source detection algorithm called SExtractor (Bertin & Arnouts 1996) to produce a catalog of source positions on the sky with corresponding FUV and NUV source magnitudes calculated for each observational visit. Source magnitudes derived from the use of a fixed 12 arcsec diameter aperture with SExtractor were utilized in this study, since these are more appropriate for isolating flux from stellar sources rather than galaxies. The source detections within each exposure at each sky-field position on the sky appear as source lists in the archives database of the MAST.

Comparison software was then run on the MAST source list catalog to reveal objects that we deemed as being time variable. This procedure involved the following four steps that were applied to each of the individual exposures of every source detected within each of the 169 sky fields. (1) First, only objects brighter than NUV magnitude $m_{\text{NUV}} = 21.0$, that were also located within 0.55° of the center of each GALEX field were selected. Such a choice lessens the influence of both degraded image resolution and “detector edge effects” that can potentially cause artifacts in the data. The choice of the magnitude limit was based on ultimately being able to maximize the number of truly variable sources while minimizing a far larger number of spuriously variable fainter sources. Targets within this selected area that were flagged by the GALEX pipeline as being potential image artifacts in the MAST dataset were also rejected. The result from this search was a list of sources, sky positions, and values of NUV (and FUV) magnitude that were found within each exposure associated with each of the 169 sky fields. (2) A comparison was then performed on all values of $m_{\text{NUV}}$ that were obtained for each source from the various exposures of each of the sky fields. Since the listed source positions each have an inherent measurement error of $\sim \pm 3$ arcsec (Morrissey et al. 2005), we restricted the comparison to sources listed within a 10 arcsec diameter error circle of the nominal source position. Only sources that varied by $>0.6$ NUV magnitudes within this error circle were selected as being potentially time variable. This variability criterion corresponds to a $>3\sigma$ change in the photon statistical error assigned to each source by the GALEX data pipeline. However, we note that for faint sources the GALEX systematic error (which is due to the combined effects of sky subtraction, flat fielding and scattered light subtraction) is far larger than the photon statistical error (Morrissey et al. 2005). Thus, the choice of $>0.6$ NUV mag. significantly minimizes the number of false variability detections. We note that the photometric stability of GALEX assessed during the 2003–2006 period is $<0.1$ mag (Morrissey et al. 2007). (3) When available, a comparison was also made with the corresponding FUV magnitudes, $m_{\text{FUV}}$, for each exposure of the sources previously identified in step 2. If the selected source is also varied by $>0.4$ FUV magnitudes, then this was deemed a confirmation of true source variability. In cases where no FUV data were available, step 3 was omitted. (4) The previous two steps resulted in a list of NUV (and/or FUV) source magnitudes with their associated sky positions recorded at a given epoch for each exposure of the various sky fields. Each of these source lists was then plotted (as epoch versus magnitude) and the individual light curves visually checked for the plausibility of astronomical source variability. The images of individual GALEX visits were also visually checked as a final verification that the source flux variation was not caused by some image anomaly. A typical anomaly in GALEX images is scattered light leakage caused by bright objects positioned just outside of the instrument field of view. In Figure 2 we show two GALEX images recorded for the ELAIS-N1 field, taken 2.5 months apart. The fuzzy horseshoe-like feature to the left of center of the 2005 May 3 image is due to scattered light and is seen to re-appear in the 2005 July 24 image with a greatly reduced intensity at a different angle to the two central bright objects, due to the different roll angle used in this pointing of the GALEX instrument. Finally, we also ran a search for FUV source variability that was not accompanied by any appreciable NUV variability. This entailed running steps 1 and 2 within the constraints of $m_{\text{FUV}} < 22.0$ and an FUV magnitude variation of $>1.0$ mag.

The list of 410 resultant time-variable UV sources is given in Table 2. In Column 1, following the format of the GUVV-1 catalog (Welsh et al. 2005), we list a unique identifier for each source that contains its GALEX mean right ascension (J2000.0) in hours, minutes, and decimal seconds and its corresponding declination (J2000.0) in degrees, arcminutes, and decimal seconds. In Column 2 we list, when available, the USNO-B1.0 all-sky catalog designation in italics (Monet et al. 2003) or the Sloan Digital Sky Survey (SDSS) DR6 designation in Roman typeface (Adelman-McCarthy et al. 2007). For objects that appear in the SIMBAD on-line astronomical catalog, in Column 3 we list their source identification. In Column 4 we list, when known, the most likely astronomical source type for the source. Criteria used to make this latter determination were

### Table 1

| Field                  | Survey | Visits | R.A.   | Decl.   |
|------------------------|--------|--------|--------|---------|
| CARINA_DPH             | NGS    | 24     | 100.36 | -51.31  |
| CCS_DSACIÓN37          | DIS    | 20     | 283.96 | 11.88   |
| CCS_Q2233              | DIS    | 25     | 339.04 | 13.94   |
| CDFS_00                | DIS    | 61     | 53.13  | -27.87  |
| CDFS_02                | DIS    | 21     | 52.01  | -28.21  |
| CDFS_03                | DIS    | 22     | 54.17  | -27.31  |
| CDFS_04                | DIS    | 14     | 52.93  | -28.91  |
| CDFS_05                | DIS    | 14     | 52.11  | -27.28  |
| CDFS_07                | DIS    | 16     | 52.10  | -29.21  |
| CDFS_08                | DIS    | 17     | 53.10  | -29.40  |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 1. Distribution of the GUVV-2 catalog sources on the sky.
generally varied, but (for the brighter sources) are mainly based on either their SIMBAD catalog identifications or on inspection of their GALEX UV light-curve data (gained from step 4 of the data search). The majority of these variable sources have no known associated source type, but when known we list source types in the following 11 categories: quasar stellar objects (QSOs), Seyfert 1 galaxies (Sy1), active galactic nuclei (AGNs), BL Lac objects (BLL), ordinary galaxies (Gal), RR Lyrae stars (RR*), X-ray sources (X), variable stars (V*), double stars (**), novae and dwarf novae (Nov), and dMe flare stars (Fl*).

In Column 5 we list the name of the GALEX sky field in which the variable source was found. In Column 6 we list the total number of detections (NUVdet) of the variable source within the associated set of NUV observations of the GALEX sky field. Column 8 lists the maximum observed NUV magnitude (NUVmax) for the source (measured in a single exposure) and Column 9 lists the variation between the corresponding maximum and minimum NUV magnitudes (i.e. ∆NUV). Similarly, Columns 10–13 list the equivalent number of detections (FUVdet), maximum magnitude (FUVmax), and variation in magnitude (∆FUV) for the FUV channel. We emphasize that the non-detection of a source previously observed in both (or one) of the two UV-bands can be attributed to either intrinsic variability (i.e., an astrophysical effect) or being due to one of the detectors having been turned off during a particular observation for instrument safety reasons. Finally, in Columns 14–16 we list (in Roman typeface) the respective g, r, and i photometric point-spread function (PSF) magnitudes as recorded by the SDSS catalog (Adelman-McCarthy et al. 2007) for the source designation listed in Column 2. Finally, we note that this new GUVV-2 catalog also includes some of the variable sources listed in the GUVV-1 catalog, often with different magnitude changes. This is due to either a greater number of observations per source being presently available for analysis, or the improvement in the source detection algorithms of Version 5.1 of the GALEX data pipeline software. For sources that have no or uncertain SDSS photometric magnitudes, we list the available USNO-B B, R, and I magnitudes in italics.

3. DISCUSSION

In this section we analyze some of the statistical properties of the 410 UV variable sources listed in Table 2. The present sample of variable sources has been discovered through observations covering a total area of ≈161 deg$^2$ on the sky, with the vast majority of the fields being located at galactic latitudes well away from the galactic plane. The previous GUVV-1 study of Welsh et al. (2005) detected 84 variable sources contained within a far larger area on the sky of ≈3000 deg$^2$. The larger area covered was due to the use of many All-Sky Imaging Survey (AIS) fields recorded during the initial survey phase of the GALEX mission. The current GUVV-2 detection rate is ≈2.6 variable UV sources per deg$^2$. This can be directly compared with a GUVV-1 detection rate from DIS pointings of ≈1.2 variable sources per deg$^2$. The increase in the present detection rate is due to improved variability search software and the generally longer time series of exposures over which variability could be assessed within the currently observed fields.

3.1. Variability Statistics

In Figure 3 we plot the respective maximum changes in UV magnitude, NUVmax, and FUVmax as a function of the number of sources exhibiting such variability. Although we see a maximum number of NUV variable sources with ∆NUV = 0.6 mag, the sharp cut-on in this source distribution is due to our definition of NUV variability as being greater than 0.6 mag. Unfortunately selecting an NUV magnitude variability less than this value results in a very large number of false detections, particularly...
| GALEX         | SDSS or USNO-B1 | SIMBAD            | Type          | Field        | N_{det} | NUV_{max} | ∆μ | FUV_{max} | ∆μ | g or B | r or R | i or I |
|--------------|-----------------|-------------------|---------------|--------------|---------|-----------|----|-----------|----|--------|--------|-------|
| J001437.6-392632.2 | 0505-0002317    | GI2_057001_NGC55  | 19            | 19.38        | 0.70     | 0         | ... | ...       | 18.22 | 17.46  | 18.09  |
| J001530.6-384855.9 | 0511-0002596    | GI2_057001_NGC55  | 19            | 19.02        | 1.72     | 6         | 20.34 | 3.45      | 15.86 | 13.87  | 13.39  |
| J001611.6-392721.5 | 0505-0002614    | GI2_057001_NGC55  | 19            | 16.16        | 2.02     | 16        | 17.59 | 5.81      | 14.91 | 13.75  | 13.95  |
| J002147.4+000031.3 | J002147.52+000030.9 | RX J0021.7+0000 | X WHTDF_00   | 24           | 20.18    | 0.67      | 24   | 20.16     | 1.07  | 19.58  | 19.18  | 18.28  |
| J002442.4+165808.0 | 1069-0004486    | GI1_022001_CL0024p1654 | 8           | 17.68        | 0.71     | 1         | 22.79 | ...       | 13.62 | 13.03  | 12.67  |
| J002904.4-425242.9 | 0471-0004614    | ELAIISC15 J002904-425243 QSO | ELAISS1_08 | 26           | 19.88    | 0.92      | 22   | 20.66     | 1.86  | 20.00  | 19.43  | 18.54  |
| J002906.7-423904.2 | 0473-0006317    | ELAISS1_08        | 29           | 18.40        | 0.66     | 24        | 18.96 | 0.93      | 19.78 | 19.05  | 18.74  |
| J003017.4-422446.3 | 0475-0007085    | QSO B0027-426 QSO | ELAISS1_08   | 16           | 18.07    | 0.63      | 11   | 18.54     | 0.96  | 19.13  | 18.26  | 18.49  |
| J003043.0-422747.7 | 0475-0007155    | QSO               | ELAISS1_08   | 29           | 17.25    | 1.48      | 18   | 19.92     | 3.73  | 15.84  | 14.53  | 14.44  |
| J003215.4-425344.3 | 0471-0005077    | QSO               | ELAISS1_08   | 29           | 20.08    | 0.75      | 24   | 20.74     | 1.62  | 19.56  | 20.03  | ...    |

**Notes.** PQ in Column 4 denotes a “possible quasar” determined from GALEX and SDSS photometry, as described in the text.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
for sources with NUV magnitudes fainter than NUV = 19.0. In the case of (associated) FUV source variability we see a maximum number of sources at ΔFUV = 0.9 mag. In Figure 4 we plot values of NUVmax versus FUVmax for these sources and find that the great majority of targets lie within ±1 mag of a straight line of slope +0.91. This is very similar to the results found for the far smaller sample of UV variable sources in the GUVV-1 catalog (Welsh et al. 2005). We note the large number of sources with peak FUV and NUV magnitudes > 20.0 that deviate more than this value from the best-fit line, and this is due to the larger measurement errors associated with these faint sources.

Of the 410 variable sources in Table 2 only 114 have astronomical identifications listed in the SIMBAD database. Of these sources, 77 (i.e. 67%) can be categorized as active galaxies (i.e. QSOs, AGNs, BLL, or Sy1). The next largest groups are those of X-ray sources (19), RR Lyrae stars, (6) and novae (3). Although active galaxies are the largest group of identified sources, it is highly probable that many of the remaining 296 uncategorized variable sources are of a stellar origin. This is mainly due to the poor coverage of astronomical identifications in the SIMBAD database for faint stellar sources as opposed to that for active galaxies.

3.2. RR Lyrae Stars

GALEX has been shown to be a sensitive probe of the flux variability observed toward RR Lyrae stars, since these stars can vary by up to 6 mag at FUV wavelengths (Wheatley et al. 2005). Using the known UV variable sources listed in the GUVV-1 catalog, Browne (2005) found that plots of (g − r) versus (u − g) SDSS magnitudes revealed a segregation of stellar sources that could be readily identified with RR Lyrae and δ Scuti-type stars. In Figure 5 we have produced a similar plot of (g − r) versus (u − g) SDSS magnitudes for the present GUVV-2 set of variable sources listed in Table 2. The box drawn in this figure (i.e., 0.99 < (u − g) < 1.28 and −0.20 < (g − r) < +0.31) contains 36 sources, all of which are listed separately in Table 3. Only 11 of these sources are previously known RR Lyrae stars (i.e., HL Her and V851 Her), and in Figure 7(a) we show the magnitude–phase light curve for the newly discovered RR Lyrae star, SDSS J081226.4+033201.1 which has a period of 0.555 days. This type of UV observation, when used in conjunction with ground-based ROTSE data, can be used to constrain Kurucz stellar atmosphere model parameters such as stellar temperature and metallicity for RR Lyrae stars (Wheatley et al. 2005). Finally, we note that Table 2 also lists four previously known RR Lyrae stars (with SIMBAD identifications) that are not shown in Figure 5. These stars, which have had their RR Lyrae status confirmed by other means, have not been included in Table 3 since their SDSS color magnitudes are not available.

3.3. AGNs and QSOs

As previously stated, the largest group of known UV variable sources in Table 2 is active galaxies. Quasars, blazars, BL Lac, and Seyfert galaxies have long been known to exhibit flux variability at all observed wavelengths from radio to gamma rays, lasting over timescales of weeks, days, or hours (micro-variability). Flux variability studies, particularly at X-ray wavelengths, have been used to provide clues to the sizes and structure of the emission regions producing the observed...
variable level of radiation. The non-thermal emission from the nuclei of active galaxies reveals itself as a flat UV-to-optical continuum spectrum, with the probable origin of the nuclear activity arising around a supermassive black hole situated in the center of the host galaxy which accretes gas from the host. During this process, gravitational binding energy is released, part of which is transformed into the UV radiation observed by GALEX. A typical UV spectrum of a low-redshift blazar is given in Pian et al. (2005), with the majority of the flux being contained in the emission lines of Si IV, C IV, and C III superposed on an underlying continuum in the GALEX FUV channel. The GALEX NUV channel contains no strong emission lines with only UV continuum emission being observed from these sources.

Although we are currently unable to positively determine which of the sources listed in Table 2 are true blazars, since the number of currently known objects is small (especially so for the southern Galactic hemisphere), we believe it useful to produce a list of possible blazar candidates for subsequent study and confirmation at other wavelengths. Both Seibert et al. (2005) and Bianchi et al. (2007) have attempted to isolate low-redshift QSO candidate sources in the GALEX data archive from color–color diagrams that use both UV and SDSS color magnitudes. In particular, plots of $(m_{FUV} - m_{NUV})$ versus $(m_{NUV} - r)$ colors can provide a very helpful discriminant between hot UV bright stars and low-redshift QSOs. In Figure 6 we show such a color–color plot for all objects in Table 2 that possess both an SDSS $r$ color magnitude and which exhibit variability in both the FUV and NUV channels. Sources previously identified as QSOs in SIMBAD are plotted as filled circles, and those without previous identification are plotted as open circles. Following the work of Seibert et al. (2005) and Bianchi et al. (2007), it is highly probable that sources lying within the region bounded by $-0.5 < (FUV_{max} - NUV_{max}) < 1.5$ and $(NUV_{max} - r) < 2.0$ are low-redshift QSOs or possibly blazars. We have identified these 35 objects in Table 2 (see footnote to Table 2). This sample could possibly be contaminated by a few cataclysmic variable stars but, as discussed in Bianchi et al. (2007), such objects are quite rare compared to the observed space density of QSOs. Finally, we note that the group of sources in Figure 6 that possess $(FUV_{max} - NUV_{max}) > +2$ is most likely to be variable main-sequence objects.

3.4. Some Interesting GUVV-2 Objects

Of the 410 objects listed in Table 2, three sources stand out as being of particular interest. These are (i) the contact binary system of SDSS J141818.97+525006.7, (ii) the eclipsing dwarf nova system IV UMa (SDSS J104356.72+580731.9), and (iii) the highly variable unidentified source SDSS J104325.06+563258.1.

In Figure 7(b) we show the NUV light curve for SDSS J141818.97+525006.7, which is a contact binary system listed in the catalog of Gettel et al. (2006). This type of highly evolved system, often referred to as W Ursae Majoris (W UMa) variables, consists of two very close binary stars whose outer atmospheric surfaces share a common envelope. Noting that there are two eclipses per cycle in the phased UV light curve, and we derive a period of 0.29064 d for this system which can be compared with that of 0.29082 d obtained from visible data. Finally, we note that the period for this system is very close to that of 0.27 d, which Rucinski (2007) cites as the maximum of the period distribution for all known W UMa systems.

IY UMa is one of the few known eclipsing dwarf nova systems of the SU UMa type, consisting of a white dwarf which accretes matter via a Roche lobe flow from a late-type donor star (Uemura et al. 2000). Such systems typically undergo series of both short (days) and long (weeks) outbursts. The GALEX data, shown in Figure 8(a) represent the first UV observations of this system, in which a variability of $\sim 1$ mag has been detected over a set of several observations spanning $\sim 1$ year. Previous visible spectrophotometric and spectroscopic observations of this system have revealed both normal and super-outbursts which have been successfully modeled by Patterson et al. (2000) and Rolfe et al. (2005).

Finally, in Figure 8(b) we show sets of NUV and FUV observations of the highly variable source SDSS J104325.06+563258.1 recorded with GALEX over a 24 month time frame. This source appears to possess FUV and NUV “quiescent” magnitudes of $\sim 20$ mag, as measured during two observations some 450 days apart, followed by two flare events which caused an increase of $> 2$ mag. Although the temporal coverage of these outbursts is not contiguous, the data do allow us to note that there was a rise of 3.7 mag in the NUV in 40 days and on one occasion there was a drop of $\sim 2$ mag in both the NUV and FUV channels in only 21 h. Its SDSS ugriZ magnitudes are all similar, suggesting a flat spectral shape in the visible region, which would preclude its identification as a flaring M-dwarf star. Although ground-based spectroscopic observations are required to provide a firm identification for this source, it is probably a previously unknown distant dwarf nova system.

3.5. Future Studies

The great majority of the presently detected variable sources will require follow-up spectroscopic study in order to reveal their true physical identity. However, it is clear from the 114 sources that already have previous identifications that the GUVV-2 catalog will be a very useful tool in the study (and identification) of the UV variability of active galaxies.
All of our present variable source detections have been based on their orbit-to-orbit variation in UV magnitude. The present study has not used the photon data from each source to search for variability on timescales of the order of seconds. Previous studies of time-tagged photon data from 1800 GALEX images have revealed short-term (<100 s) UV flare events from 49 newly identified dMe stars (Welsh et al. 2007). Future inspection of the photon data from the entire GALEX database could enable studies of a variety of new source phenomena that includes the possible detection of stellar transits by Jupiter-sized exo-planets and the study of short-term flare outbursts from cataclysmic variable systems.

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Facilities: GALEX

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